THESIS / THÈSE

DOCTOR OF ECONOMICS AND BUSINESS MANAGEMENT

Essays on strategic procurement in an increasingly competitive environment

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Award date:
2018

Awarding institution:
University of Namur

DÉPARTEMENT
SCIENCES DE GESTION

UNIVERSITÉ DE NAMUR

DeFiPP

Essays on strategic procurement in an increasingly competitive environment

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Graphisme de couverture : © Presses universitaires de Namur

Rempart de la Vierge, 13
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Imprimé en Belgique
ISBN : 978-2-39029-007-0
Dépôt légal: D/2018/1881/13

Acknowledgments

First, I would like to express all my gratitude to my advisor, Professor Aadhaar Chaturvedi, for his permanent support during my Ph.D study, for his involvement, for his patience, for his passion and for the pertinence of his comments. His guidance has been an inexhaustible source of inspiration not only for my research, but also for numerous other dimensions of my professional and private life. I measure the chance that I have had.

Besides my advisor, I would like to thank the other members of the jury for the time spent on reading the thesis, as well as on attending the private and public defenses. Their insightful comments and suggestions have greatly contributed to improving the manuscript, to envisaging new opportunities to extend the current research, and to complementing my vision of a high quality research process. I am particularly grateful to the external members of my research committee, Professors Robert Boute and Philippe Chevalier, for their presence, their input and their encouragements along my doctoral studies.

At the time of concluding a chapter of seven years at the university of Namur, I have also a warm thought for all my former and present colleagues. In different ways, they all contributed to this thesis through their help, their support and through the passionating discussions that we have had together. I address a specific thanks to my co-author, Wenli Peng, for the fruitful collaboration.

Finally, it is natural to thank my family, my in-laws, as well as all of my friends who have been indirectly part of this adventure through their permanent support. I am particularly grateful to my parents, for their everlasting caring, and to my future wife, Méelanie, for her patience and her presence.

Contents

1. Introduction of the dissertation

1.1 Functions of strategic procurement and current business environment

This dissertation focuses on procurement. Procurement is a critical activity of the production process supporting the mission of a firm in 3 principal ways. (1) First, procurement ensures the firm's product availability, through enabling production continuity. For this, a sufficient amount of components with the right specificities has to be available at the right moment to prevent production stoppages and consequent missed sales. The well-known example of Ericsson illustrates that a persisting disruption of supply can result in dramatic consequences for the buying firm. We consider that product availability also encompasses flexibility (to respond to demand changes, for example), as this requires supply to be available at the right moment. (2) Procurement also plays a major role in making a firm's final product cost competitive by trying to complete the previous function at the lowest cost possible. Since procurement costs often account for more than half of a product total cost, procurement clearly has a critical impact on the bottom line of a firm. (3) In addition to those two historical missions, procurement is increasingly expected to bring added-value into a firm's finished good. For this reason, procurement does not only belong to the supply chain, but also to the value development chain, as illustrated on Figure 1. More specifically, procurement has to select the right suppliers to source durably external expertise that would ensure the firm's product quality, reliability, innovation, etc... Notably, the quality and the reliability of the product would greatly depend on the components procured that compose the product. Introducing poor quality components into a product can oblige a firm to take costly corrective actions, such as recalling products (like in the case of Toyota cars because of Takata airbags exploding unexpectedly), in addition to damaging the brand image. With the same logic, procurement has also some responsibility in the innovation process to secure not only present, but also future market shares.

To fulfill those three functions, the procurement activity constantly needs to adapt to the business environment in which it takes place, which is nowadays characterized by an extremely intense competition. Factors like globalization, improved transportation and information technologies have strengthened competition through allowing firms to target any customer in the world, hence turning local markets into global ones such that only the most competitive firms can subsist. On the other hand, those factors have also offered buying firms an easy access to virtually any supplier on the planet, including the most efficient ones. This has motivated firms to increasingly outsource components that a supplier can do better or cheaper, and focus their resources on their own core competencies (Gottfredson *et al*, 2005), rather than using old-fashioned vertically integrated structures. Beyond components procurement, more capabilities and functions that were historically managed by the firm itself are now devoted to suppliers, making the procurement division bearing a greater responsibility for the activities of the firm, and notably for the end-product differentiation. As an illustration, a survey from Accenture (2015) emphasizes that some firms expect their suppliers to use their expertise to lead the innovation process. Therefore, while outsourcing provides some expertise and cost benefits, notably, it also broadens the scope of action of procurement, as it requires additional supplier investigation, selection and integration. Moreover, it further complicates the procurement role by multiplying the supply (and development) chain linkages and by reducing the control that a firm has on each of these linkages (as compared to vertically integrated structures). The current business environment further affects the procurement role along (notably) three directions. First, the emergence and the development of China, India and other Asian countries as unavoidable low-cost production hubs resulted in more spread supply chains and longer lead times, which limit supply chain agility. Second, the lean philosophy has strongly influenced procurement practices by reducing redundancy in inventories, in suppliers and in capacity, resulting in both more efficient and more exposed (to disruption risk) supply chains. Third, events like geopolitical conflicts, social unrests or natural disasters occur more frequently than in the past, and often have important macroeconomic consequences, such that the prevailing global uncertainty is higher than it has ever been.

In conclusion, the environment is characterized nowadays by more competition, more complex supply chains, less ability to absorb shocks, higher risk of disruptive events and higher expectations for procurement.

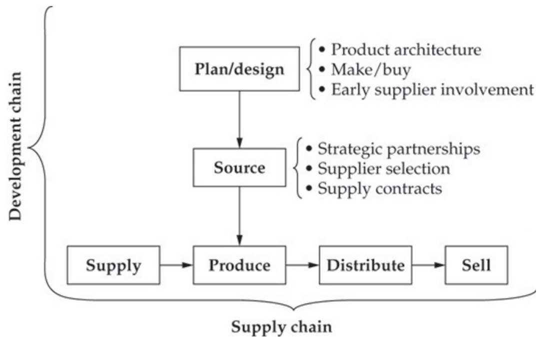

Figure 1: The enterprise development and supply chain (Simchi-Levi *et al.*, 1999).

In such context, procurement managers are more challenged than ever to obtain continuous supply with the right requirements and at a competitive price. However there are many procurement levers that they can utilize to cope with this situation (e.g. supply diversification, supplier development, procurement auctions, etc...). While some of these levers could be complementary, some others would not be. The role of the procurement is therefore to decide which levers to activate, and how to activate these consistently with each others, in order to define a procurement strategy that would address the three procurement functions in supporting the firm's mission. In particular, because each category of item procured has its own requirements, it also deserves a specific strategy. Following this, we observe in practice an ever widening gap between operational suppliers, managed in a procedural manner, and key suppliers, which become an extension of the firm (Accenture, 2015). In conclusion, more is required from the procurement activity in a more demanding environment. To turn this threat into an opportunity, procurement has shifted from an operational activity to a strategic activity.

Our thesis attempts to provide guidance on how to strategically manage some procurement levers as a mean to derive comparative advantages. To better visualize how the thesis contributes to the vast literature in procurement, we first identify the current trends in the procurement levers (as well as their strategic implications) enabling firms to organize their supply and value development chains such that they can develop comparative advantages in the prevailing environment. For this, we review in the next subsection the procurement literature and present the

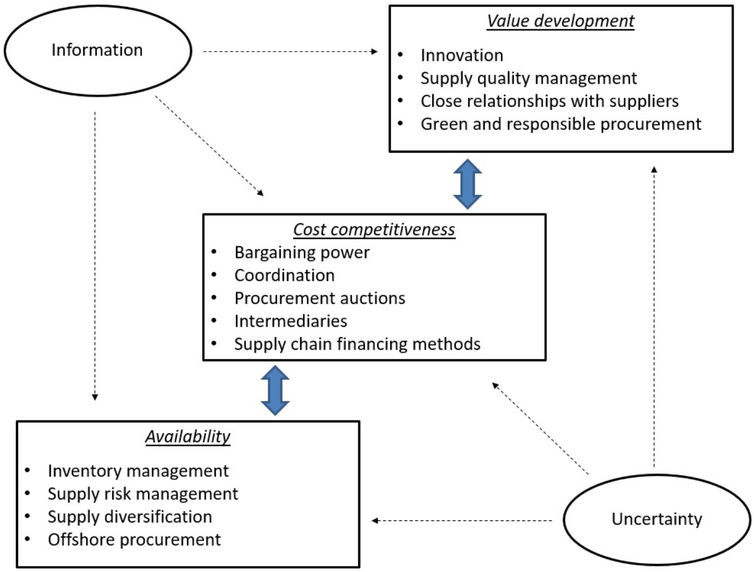

Figure 2: Framework of the main procurement strategic levers investigated in the recent OM literature.

main levers according to the procurement function that they principally support. We summarize this literature in a framework depicted in Figure 2. This framework is then used to position our different chapters in the current literature. Note that the cost competitiveness function of procurement is interrelated with the two other functions, as shown by the double-sided arrows. This is because improving supply availability and developing value often imply extra expenses and hence threaten the cost competitiveness function of procurement. It follows that there is a constant trade-off between the cost of a final product and its availability or value.

1.2 Trends in procurement

Procurement levers related to product availability

We start describing the current trends in procurement by discussing procurement levers that enable to manage product availability. Under normal conditions, ensuring product availability for end customers is not an issue, but as uncertainty keeps growing, it becomes increasingly challenging. We first study the procurement levers enabling a firm to tackle demand variability, and then present those that can be useful under supply uncertainty. Finally, we examine offshore-procurement, which is related to both demand and supply uncertainty. When a buyer faces demand uncertainty for its product, it needs sufficient available supply to adapt its production such that it can respond to these demand variations. For this, the buyer can either maintain expensive inventories, or somehow outsource this costly function to its suppliers. We designate the various buyer's options as **inventory management**, which is the first procurement lever that we examine. The first option for a buyer to be responsive to demand changes is to maintain sufficient inventory levels. The supply chain costs incurred by inventories can be reduced through vertical information sharing along the supply chain (Cachon and Fisher, 2000). Especially, it has been largely documented that supply chain participants sharing demand information can reduce the *bullwhip effect* (Lee *et al.*, 1997a, 1997b; Lee *et al.*, 2000; Chen *et al.*, 2000). There is a vast literature on inventory decisions (see notably Williams and Tokar (2008) for a review) and on the bullwhip effect. Given its important size and since it is not directly related to our projects, we do no further detail it.

Since more and more capabilities tend to be outsourced to the supply base, buyers often prefer to limit their own inventories and rely on their suppliers to either maintain inventories, or to be sufficiently reactive by disposing of enough capacity. The latter option enables to substitute the buyer's inventory risk into a supplier's capacity risk, which can be achieved through a pull (rather than a push) contract (Li and Scheller-Wolf, 2011). However, if the buyer maintains low levels of inventory but depends on its suppliers' capacity, it has to motivate supplier investments in capacity. Before the supplier makes its capacity investment decision, the buyer has an incentive to inflate its demand forecast to ensure sufficient supplier's investments in capacity, which results in the supplier considering the buyer's forecast as non credible. Incentivizing sufficient capacity investments from the supplier through a credible demand forecasts signal can be achieved by the buyer through adequate contracts (Cachon and Lariviere, 2001; Tomlin, 2003; Özer and Wei, 2006; Taylor and Plambeck, 2007a, 2007b) or through building trust between agents (Özer *et al.*, 2011). Sharing capacity investments with the suppliers is another possibility for the buyer to motivate suppliers' investments in capacity, even though it can be inefficient if resulting in capacity over-investments from the suppliers (Hu *et al.*, 2017). Rather than using the full capacity of a single supplier, a buyer can also use several sources for a specific component, in order to increase the overall capacity of its supply base (Burke *et al.*, 2007; Feng, 2012; Gao *et al.*, 2017). To deal with demand variability and preserve supply chain responsiveness, the buyer can finally rely on suppliers' inventory levels. In that case, suppliers' inventory levels influence the supplier selection (Jin and Ryan ,2012), as well as the buyer's order size decision (Craig *et al.*, 2016; Jain *et al.*, 2017).

The greater exposure of supply chains to supply disruptions, in parallel with the greater risk of occurrence of a disruptive event, has resulted in abundant research dealing with procurement levers aiming at managing the uncertainty arising from the supply side, which we regroup under **supply risk management**. Supply risk can result either from firm-specific uncertainty or from systemic uncertainty (i.e. the uncertainty is out of the control of the firm and threatens many firms). While the first chapter of this dissertation widely discusses the procurement strategies enhancing supply chain resilience to systemic disruptions, it is less focused on firm-specific risk, for which we therefore provide complementary references. Recent investigations on supply risk notably include inventory decisions adjusted to cope with unreliable suppliers (Dada *et al.*, 2007), buyer's long-term commitment with a disruption prone supplier (Swinney and Netessine, 2009; Gao, 2015), buyer's subsidy decision while taking into account the supplier financial health specific situation (Wei *et al.*, 2013; Babich, 2010) and procurement decisions when the buyer and the supplier have asymmetric information about the risks of disruption (Chen, 2014). From a different perspective, Hendricks and Singhal (2014) empirically investigate three types of causes for supply-demand mismatch (i.e. production disruption, excess inventory and product introduction delays) which can affect equity volatility. Further information on supply risk management can be obtained in the following literature reviews: Tang (2006), Sohdi *et al.* (2012) and Snyder *et al.* (2012).

We next document another procurement lever related to supply risk management, namely **Supply diversification**. This has catalyzed recently more attention in the literature than any other subject related to supply risk. Supply diversification actually supposes that a buying firm does not source all its supply (for a specific component) from the same supplier, in order to spread the supply risk over two or multiple suppliers. The main benefit of a diversification strategy is thus to incorporate supply risk considerations in the procurement order decision, rather than simply focusing on cost. This trade-off between procurement cost and supply risk has been examined in many different contexts, including buyer learning about the yield of an unreliable supplier from their past experiences (Tomlin, 2009), supplier unreliability (Federgruen and Yang, 2009; Li *et al.*, 2013), correlated suppliers random yields (Tang and Kouvelis, 2011), buyer's preference ordering constraints based on non-price attributes (Honhon *et al.*, 2012), asymmetric suppliers in fixed and variable costs (Zhang *et al.*, 2012), supplier private information about its own disruption probability (Yang *et al.*, 2012), correlation across two substitutable resources that are disruption prone (Sting and Huchzermeier, 2014), risk of complete disruption threatening only some of the potential suppliers (Hu and Kostamis, 2015) and suppliers asymmetric reliability (Li *et al.*, 2017). However, it is critical, for a buyer diversifying its supply, to have visibility on its direct suppliers' supply network, in order to avoid overlap or interdependence among lower tiers suppliers, which could erase the diversification benefits (Ang *et al.*, 2017; Chen and Guo, 2014; Choi and Krause, 2006). Interestingly, some authors have also compared the supply diversification benefits with those of other supply risk mitigation strategies, such as supplier investments in capacity restoration (Hu *et al.*, 2013) and buyer's direct (subsidy) or indirect (inflated order) investments in its preferred supplier reliability (Tang *et al.*, 2014), while others have examined the interactions, when used simultaneously, between diversification and the two other main mitigations strategies: excess capacities and safety stocks (Chaturvedi and Martínez-de-Albéniz, 2016).

Finally, **offshore procurement** is related to both demand uncertainty and supply uncertainty. Whereas the low labor costs of some Asian countries, like China, have for long justified to source from overseas suppliers, the difference in these labor costs between China and the US have significantly reduced over time (George *et al.*, 2014), such that firms pay a greater attention to the disadvantages from offshore purchasing in managing their global sourcing. In addition to several supply risks (e.g. increased risk of disruption or quality), the main disadvantage of offshore procurement, largely documented in the literature, is the loss in supply chain responsiveness (or flexibility) to demand changes, notably because of longer distances between supply chain participants. Offshore procurement is therefore not necessarily detrimental to supply availability, but rather to supply flexibility. To counterbalance this lack of flexibility underlying offshore procurement, higher inventory levels can be maintained, even though this would erode the cost benefits from this strategy (Jain *et al.*, 2014). A diversification strategy could then be attractive, in order to balance the cost benefits from offshore procurement and the supply chain responsiveness from local procurement. Boute and Van Mieghem (2015) compare single-sourcing and diversification strategies when the buyer disposes of a responsive local supplier and a cheap offshore supplier, while considering the implications in terms of procurement cost, flexibility and inventories. Other authors focus on rather similar situations, but focusing on specific factors, such as supply yield uncertainty (Kouvelis and Li, 2013), suppliers with limited capacities (Tan *et al.*, 2016), short life-cycle products (Calvo and Martínez-de-Albéniz, 2016) or costless returns (Janakiraman and Seshadri, 2017). Peng *et al.* (2012), Kouvelis and Tang (2012), Wu and Zhang (2014), as well as in Gong *et al.* (2014) have also contributed to this literature. Most of the research dealing with offshore procurement uses the example of US firms sourcing from China. It is well known that with the labor costs rising in China, US firms have largely considered reshoring jobs back home, as studied by Chen and Hu (2017), or nearshoring these in a close country as Mexico (Allon and Van Mieghem, 2010). The latter option represents a great compromise between cost and flexibility. The risk related to supply quality in offshore countries has also been advanced to motivate reshoring (or nearshoring), as in Gray *et al.* (2011) or in Ancarani *et al.* (2015).

Procurement levers related to product cost competitiveness

Other procurement levers aim at improving a product cost competitiveness. A first dimension on which a buyer can play to make procurement costs savings resides in fully exploiting its **bargaining power** with its supply base. This can be achieved by multi-division firms through centralizing and coordinating their procurement activity (Balakrishnan and Natarajan, 2014). On the contrary, abusively outsourcing might lower a buyer's bargaining power, as it decreases the volume ordered and hence the leverage on some suppliers (Ellram and Billington, 2001; Kayiş *et al.*, 2011; Chen *et al.*, 2012). Rather than optimizing its bargaining power, the buyer can rather concentrate on limiting its suppliers' bargaining power through adequate contracts (Feng and Lu, 2012, 2013). The outcome of a bargaining process can also be affected by situational factors, including repeated buyer-supplier interactions in a context of dynamic negotiations (Martinez-dé-Albeníz and Simchi-Levi, 2013) or the possibility for complementary suppliers to form negotiation alliances (Nagarajan and Bassok, 2008). We finally mention Lovejoy (2010), who examines supply chain efficiency and profitability when bargaining occurs at different echelons of the supply chain.

Another procurement lever that can be actioned is the appeal to **intermediaries**. First, as further discussed in Chapter 3, firms can utilize group purchasing organizations (Nagarajan *et al.*, 2010) or join buying groups (Nollet and Beaulieu, 2005) to obtain more attractive financial conditions from their suppliers through benefiting from the higher bargaining power of the group of buyers, relatively to this of its individual members. Sourcing intermediaries also become popular. These firms carry out the complete sourcing function by selecting and managing a base of suppliers, providing both transactional and informational benefits (Belavina and Girotra, 2012). Sourcing intermediaries can reveal being particularly useful to manage a network of low-cost international suppliers (Adida *et al.*, 2016). Intermediaries can also make the link between a risk-averse retailer and a manufacturer, in order to offer risk-reducing contracts to the retailer to incentivize this making efficient order size decisions (Agrawal and Seshadri, 2000).

Procurement spendings can further be reduced by improving the **coordination** among supply chain participants. A better coordination is often achieved with adequate contracts (Cachon, 2003; Chiu *et al.*, 2011), notably under both supply and demand uncertainties (He and Zhao, 2016), suppliers' size asymmetry (Özer and Raz, 2011), supplier and buyer's profit targets (Deng and Yano, 2016), time or/and quantity flexibility (Li and Kouvelis, 1999), revenue-sharing contracts (Cachon and Lariviere, 2005), rebates (Taylor, 2002), quantity flexibility (Tsay, 1999), or with options (Barnes-Schuster *et al.*, 2002). Typically, supply chain coordination is facilitated by credible information sharing along the chain (Chen, 2003). The exchange of information can either be voluntary, as suppliers might be better off by sharing their own production efficiency (Chen and Deng, 2015), or framed by a contract ensuring credible information sharing, from the supplier to the buyer (Çakanyildirim *et al.*, 2012; Fang *et al.*, 2014), or from the buyer to the supplier (Amornpetchkul *et al.*, 2015; Tang and Girotra, 2017).

The next procurement lever that we consider derives procurement savings through intensifying the competition across suppliers. As globalization and communication technologies have respectively increased the number of potential suppliers per component, and provided an immediate access to each of these suppliers, **procurement auctions** have rapidly become an extremely popular tool to enhance competition, especially for non-strategic and standardized items. The literature has grown in parallel and is so broad that we simply discuss topics in auctions related to some recent well-published papers (see Chapter 2 for additional references on auctions). Initially, auctions were used as a mechanism allowing buying firms to foster competition and to easily discover the lowest-cost supplier. Through time, more complex types of auctions have appeared and offer the auctioneer additional benefits, such as providing the buyer with information about its potential suppliers (pinker *et al.*, 2003). Moreover, if well designed, auctions can also incorporate non-price attributes in the selection criteria, like switching cost (Santamaría, 2015) or supplier reputation (Brosig-Koch and Heinrich, 2014), even though some non-price attributes remain difficult to be captured by classical auctions. While relational contracts can be used to deal with those non-price attributes (Tunca and Zenios, 2005), buyer-determined auctions are also possible. In these auctions, the buyer can freely select its preferred supplier after the bidding stage, with or without having announced upfront the price and non-price attributes affecting its decision (Stoll and Zöttl, 2017). As mentioned earlier, supply risk has become prevalent in the environment, which has resulted in procurement practices incorporating such risk. Auctions have followed the trend, as through a split-award auction, the buyer is further capable to balance the benefits of both suppliers competition and diversification. For such type of auctions, Bichler *et al.* (2015) and Chaturvedi *et al.* (2018) compare the theoretical and experimental outcomes under different auction formats. Finally, the literature comprehends many works examining auctions under specific situations, like auctions with price visibility and bidders quality (Haruvy and Katok, 2013), repeated auctions for components bought in sequence (Jiang, 2015), auction with business rules on the number of suppliers selected and on the amount procured from each supplier (Gupta *et al.*, 2015), or auctions (under specific auction formats) with capacity constrained suppliers (Chaturvedi, 2015). In the second chapter of this thesis, we analyze whether organizing more (or less) frequent second-price auctions would enable a firm to balance the benefits from both supplier competition and effort.

We then delve into the literature on **supply chain financing methods**, which enable to facilitate transactions along a supply chain and hence to better coordinate it (Yang and Birge, 2013). Non-classical financing methods are typically advantageous when firms are financially constrained and have no access to usual means of financing, such as bank credit. Notably, trade credit can be extended by suppliers to financially constrained buyers as these suppliers are often better informed than financial institutions about the buyers' default risk (Biais and Gollier, 1997; Petersen and Rajan, 1997), or to help the buyer managing its demand uncertainty (Cai *et al.*, 2014). Trade credit offered by the supplier to the buyer makes operational sense as the buyer might want to delay payment in order to observe the quality of the supply upfront the payment. However, in practice, the situation is often reversed with small suppliers being in need of credit to produce their supply for a bigger buyer. In that case, a buyer can play the role of intermediary between its supplier and a bank to negotiate a lower interest rate in favor of its supplier (Tunca and Zhu, 2017), or the buyer might even directly extend trade credit to its supplier (Tang *et al.*, 2017). Depending on its risk profile, the supplier might also use factoring, which implies the payment of a premium to a third-party in exchange of this financing the supply production, as well endorsing the buyer's risk associated (Klapper, 2006). It is however also largely observed that small and financially constrained suppliers extend trade credit to large buyers that do not need it. While this could be due to the buyer's bargaining power (Klapper *et al.*, 2012), or to suppliers' desire to signal product quality (Long *et al.*, 1993), Peura *et al.* (2016) investigate whether the reason would not lie in the impact of trade credit on horizontal competition among buyers. Seifert *et al.* (2012) further provide a detailed literature review on trade credit motivations (from both sides). From a different perspective, but also related to the interface between finance and procurement, Shunko *et al.* (2014) investigate the tax optimization problem when sourcing from multiple countries.

Procurement levers related to the value chain development

Through the outsourcing of multiple components and capabilities, buying firms partially transfer the control that they have on the components that constitute their products to their suppliers. This is an important issue since it is notably through those components that a firm provides value to its customers. Numerous academicians have directed their attention on the procurement levers that would compensate this loss of control, and hence assure value to customers (through end-product quality, reliability and differentiation) on both the short term and the long term. We summarize recent articles in four procurement levers based on innovation, supply quality, buyer-supplier relationships, as well as on green and responsible procurement, which are four drivers of value. We begin by analyzing the interactions between the procurement activity and the **innovation** process. Innovation is critical to create value and secure market shares in the future, such that firms extensively outsourcing from their suppliers should properly manage the collaboration with these to promote innovation. This is especially important since decentralized supply chains usually discourage investments in innovation, as compared to centralized supply chains (Gupta and Loulou, 1998; Plambeck and Taylor, 2005). To overcome this, buying firms can, on the one hand, motivate supplier investments in innovation through committing early to the price of the end-product (Gilbert and Cvsa, 2003), through favoring open technology (Hu *et al.*, 2017), as well as through promoting revenue-sharing contracts (Wang and Shin, 2015). On the other hand, buyers might rather favor a collaborative approach with the suppliers and integrate these early in new product development, which in addition enables to reduce the cost and the time to launch the product on the market (Ragatz *et al.*, 2002; Petersen *et al.*, 2003, 2005; Koufteros *et al.*, 2007; Fliess and Becker, 2006; Schiele, 2010; Henke and Zhang, 2010).

Outsourcing practices do not only threaten innovation, but also the quality/reliability of the product sold to the end customers, since the firm would have lower visibility and control over the components constituting its product. The quality/reliability of the components are however an important driver of value. Therefore, the lower control that firms might have on those components poses a certain number of challenges in terms of **supply quality management** and requires buyers to work closely with their suppliers, as a mean to avoid quality issues, which is particularly important if a failure of one component could cause the failure of other components (Agrawal *et al.*, 2017). One strategic approach to avoid quality issues is reactive and consists in setting effective supply quality verifications. Different control mechanisms have been examined in the recent literature, including suppliers voluntarily testing their own product quality (Arya *et al.*, 2014), warranty/penalty contracts (Reyniers and Tapiero, 1995; Balachandran and Radhakrishnan, 2005) and non-contractual verifications (Baiman *et al.* 2010). Some factors can also affect the effectiveness of such verifications, like rating suppliers quality risks (Zhou and Johnson, 2014), appropriately defining the timing of the controls (Handley and Gray, 2013), or yet adopting collaborative or competing warranty contracts with suppliers (Dai *et al.*, 2012). Finally, because buyers are often putting pressure on their suppliers to lower their price, these might be tempted to cut corners on quality to remain cost competitive, which is known as product adulteration. This other type of risk related to supply quality should also be managed (Babich and Tang, 2010), which is possible through deferred payment (Rui and Lai, 2015).

While suppliers and/or buyer's supply quality checks provide more confidence to the buyer in the quality of its supply, some defaults or issues could appear through time and hence be difficult to detect immediately. To limit this risk, supply quality can further be managed in a more proactive manner (which does not prevent a buying firm from further reactive verifications) through establishing **close relationships with suppliers**, or even with suppliers' suppliers (Agrawal *et al.*, 2014). By doing this, a buyer has more knowledge and visibility on its suppliers' production standards. In addition, a buyer setting up close relationships with its suppliers to master supply quality would be less likely to switch of supplier regularly, as compared to a buyer having adversarial relationships with its suppliers. As a consequence, suppliers in a close relationship with a buyer would surely obtain buyer's future business, as long as they provide satisfactory supply quality, and hence would be motivated to make efforts in improving supply quality. Even though a close relationship is an efficient lever to maintain long-term quality and reliability of external supply (and even innovation), it might not be beneficial in any circumstances (Lambert *et al.*, 1996). Namely, building close relationships can sometimes be difficult if the culture of the enterprise is not adapted, as it has been largely documented through the comparison of US and Japanese firms in their relationships with suppliers. Actually, buyer involvement and greater attention to suppliers are necessary for successful close relationships (Bensaou and Venkatraman, 1995; Liker and Choi, 2004). Simatupang and Sridharan (2002) complement this by claiming that it is not only managerial inertia, but also opportunistic behaviors that deter collaboration, despite the fact that it would coordinate the supply chain. Buying firms committed into close buyer-supplier relationships might still cooperate more closely with some suppliers by investing in supplier development, which aims at enhancing suppliers' performance and capabilities to meet the firms' future needs (Hahn *et al.*, 1990; Krause, 1997; Krause and Ellram, 1997; Krause *et al.*, 1998). Finally, even closer collaboration between a buyer and a supplier can occur through supplier integration, which implies the combination of both the buyer and the supplier's resources. While it has mostly been studied in the context of new product development (see earlier discussion), supplier integration can also be used to develop or improve processes (Wagner, 2003). In Chapter 1, we study another potential effect for the buyer of maintaining close buyer-supplier relationships. Namely, we analyze whether such type of relationship would affect buyer's resiliency to systemic supply disruptions.

The literature has identified two major threats related to outsourcing, as well as to procurement levers dealing with innovation, supply quality and close relationships. (1) Investing time and efforts in a supplier has to be done cautiously as idiosyncratic investments in suppliers might not be transferable to another supplier in case of supplier switch (Bensaou and Anderson, 1999; Kang *et al.*, 2009). More importantly, a buying firm making specific investments in a strategic supplier and disclosing sensitive information to this supplier would absolutely want to avoid that the resulting gains actually also benefit a competitor that would procure from the same supplier, which is a phenomenon known as spillover. Therefore the presence of shared suppliers in an industry directly influences the organization of the innovation across this industry or, at least, across some supply chains. Moreover, while it is sometimes argued that spillovers benefit the pool of firms that share innovation, in practice, it is observed that firms with superior knowledge lead the innovation, such that only the firms with inferior knowledge benefit from the spillovers. This phenomenon therefore reduces the cost of innovation, but also discourages investments in innovation as it could be copied by competitors (Knott *et al.*, 2009). However, R&D spillovers can also motivate the supplier in accepting to shift the R&D from the buyer to itself, since it can then value this investment nearby other buyers (Harhoff, 1996). There could further be other spillovers than those related to innovation, such as spillovers from buyer's investments in improving a shared supplier's reliability (Wang *et al.*, 2014) or supply quality (Agrawal *et al.*, 2016). In order to protect idiosyncratic investments in a supplier shared with rivals, buying firms can design exclusive capacity and first-priority capacity contracts (Qi *et al.*, 2015). These spillovers highlight the importance for a buyer of the visibility that it has on its suppliers' operations.

The other threat mentioned in the literature is (2) the loss of expertise and skills that would result from intensively relying on external suppliers. This is notably the case for the innovation process, as manufacturing inspires future innovation, such that outsourcing the complete manufacturing activity can reduce the future ability of a firm to differentiate itself from the competition, and hence to secure long-term market shares (Xiao and Gaimon, 2013). The loss of expertise could further affect other functions related to procurement than innovation. Notably, manufacturing offshoring has resulted in the loss of supply chain skills in the UK, notably, such that many firms might not be able to bring manufacturing jobs back home (Bailey and De Propris, 2014). The situation could even be worse. While contract manufacturers allow OEMs to focus on R&D, marketing or design, they also develop capabilities that might enable them to finally compete with the OEMs on their end market (Arrunada and Vazquez, 2006). As an illustration, Lenovo, which initially simply distributed IBM equipments in China, has finally engaged in a joint-venture with IBM and sells PCs with the logo of Lenovo. A similar situation can occur with suppliers rather than distributors, as these might learn by supplying (Alcacer and Oxley, 2014) and hence climb the value chain, finally competing for their initial buyer's market shares (Wan and Wu, 2017). From those two threats, it appears that developing additional value from the supply base is critical for long-term profitability, but protecting the value created and also ensuring the ability of the firm to keep obtaining value in the future are as much important.

Finally, following the general trend, **green and responsible procurement** is gaining momentum as it derives additional value for various reasons, including ethics (Carter and Jennings, 2004), cost reductions (Carter *et al.*, 2000), regulations compliance (Appolloni *et al.*, 2014) or yet brand image (Huang *et al.*, 2015; Plambeck and Taylor, 2015). For a buying firm, having in its end product a component (or having a supplier) that would not respect social or environmental standards could result in its brand name being negatively impacted. This justifies that we consider green and responsible procurement as a lever for a buyer to reach a reliable product. Several options have already been investigated to help achieving green and responsible procurement, among which buyer's commitment into a relationship with a supplier to motivate its compliance to environmental requirements (Simpson *et al.*, 2007), collaboration with small firms rather than multinationals to favor sustainability (Touboulic and Walker, 2015) and buyers' willingness to pay a premium for socially and environmentally responsible suppliers (Guo *et al.*, 2016). It is also intuitive that firms that desire to promote environmental procurement through reducing, recycling, reusing and substituting materials in their supply chain would need to better coordinate with the other participants of their supply chain (Carter and Carter, 1998). We conclude this paragraph on green and responsible procurement by referring the interested reader to literature reviews from Srivastava (2007), Hassini *et al.* (2012), Hoejmose and Adrien-Kirby (2012), Igarashi *et al.*(2013), as well as Appolloni *et al.* (2014).

Impact of uncertainty and information

In Figure 2, one can observe that uncertainty and information would affect procurement in all of its functions. Actually, uncertainty is everywhere: at the demand side, at the supply side, at the competitors side, in the environment. It goes far beyond the risk of supply disruption due to either a firm-specific event or a more systemic event. Uncertainty could arise from the ability of suppliers to innovate, from the outcome of an auction, from a negotiation process, in the quality of the supply, etc... Such uncertainty greatly complicates procurement decisions, but it is also a source of comparative advantage for the firms that manage it better than their rivals. The information management comes in parallel with the notion of uncertainty, since more information reduces uncertainty and hence improves supply chain decisions. Therefore, it is important for supply chain participants to disseminate the information along the supply chain. However, it has to be done cleverly and cautiously. While more information often results in a better coordination of the supply chain (e.g. the bullwhip effect), it might also sometimes be detrimental for one specific agent, like in group purchasing, as we show in the third chapter of this thesis. It is therefore important to ensure that each supply chain participant has the right incentives to disclose the information that would make the supply chain more efficient.

Other procurement levers

Aside the procurement levers that we have presented in the previous paragraphs, others have been mentioned in industry reports, which are regularly released by consulting firms. These complement the theoretical literature by presenting more operational challenges that procurement managers face and will face in the near future. These challenges include the implementation of cloud computing, real-time analytics, industrial internet of things, cognitive systems, digital technologies, robotics, automation, as well coping with the labor costs increase in Asia (PWC, 2012; PWC, 2013; McKinsey, 2013; Ernst & Young, 2015; Ernst & Young, 2016; Accenture, 2015; Deloitte, 2016; Deloitte, 2017). However, as the world changes faster than ever, and as procurement evolves in parallel, it is more the ability of the procurement managers to strategically adapt to the environment and to specific circumstances, rather than a blind replication of successful procurement strategies, that would enable a firm to durably develop comparative advantages through the procurement activity.

1.3 Positioning and contribution of the dissertation

In the previous subsection, we have provided an overview of the main procurement levers that a firm can use to fulfill the three principal functions of the procurement activity. While some of these levers might be managed in a complementary manner (e.g. offshore procurement and supply quality management), some others would rather be substitutes (e.g. close buyer-supplier relationships and auctions). The role of procurement is therefore to define (and implement) a strategy that would consist in deciding the combination of levers that would best serve the firm's objectives, and the specific utilization of the selected levers (i.e. the levers selected are contingent on how they can be utilized more specifically).

The variety in the available levers and in their utilization indicates that there is no recognized best practice in procurement, but rather that each situation (at a firm-component level) deserves a particular strategy. None of the papers cited actually attempts to determine which combination of procurement levers should be favored. Rather, those papers analyze how to use particular levers strategically in order to better support the firm in reaching a comparative advantage in supply availability, cost competitiveness and value development. This is also how this dissertation contributes to the literature, as we provide guidance on how to manage specific procurement levers in particular situations. Through this, we document the additional value that could be obtained from strategically using procurement levers, which could further influence the strategic selection of the procurement levers.

Specifically, the first chapter investigates how various supply chain practices related to the buyer-supplier relationship influence the ability of a buying firm to cope with supply disruptions resulting from a systemic shock. Recovering faster to supply disruptions than the competition can be an important advantage. After a supply disruption provoked by a fire at a *Philips* plant in Albuquerque, the faster reaction of *Nokia*, as compared to its competitor *Ericsson*, to secure the remaining supply from *Philips* has completely changed the dynamics of the competitive power of those two firms. In Chapter 2, we show that contract length, supplier idiosyncratic investments and supply base size interact together such that decisions on contract length and supply base size should be made consistently, in order to improve the product cost competitiveness. In the third chapter, we analyze the potential of group purchasing to further reduce production expenses, and thus increase cost competitiveness. Namely, group purchasing enables buying firms jointly purchasing to negotiate down a lower purchasing price from their common supplier, but would meanwhile result inevitably in some sensitive information being disclosed between the competing buyers. We therefore observe in which situations the gains from a lower purchasing price outweigh the cost of information leakage.

This dissertation covers the three categories of procurement levers described in our framework. Specifically, Chapter 1 mixes topics arising from supply availability and supply value development, whereas chapter 2 deals with both supply value development and supply cost competitiveness. Finally, Chapter 3 focuses on procurement levers enabling cost competitiveness. Before each of these chapters, we detail, in a foreword section, how our research projects contribute to the literature on strategic procurement in an increasingly competitive environment through answering three questions:

(1) How is the research project positioned in our framework presenting the procurement levers discussed in the recent literature?

(2) How does the research project deal with the current business environment?

(3) What is the strategic dimension of the research project?

The remainder of this dissertation is therefore organized in the following manner: we present each chapter preceded by a foreword subsection, before concluding and providing the references of this introduction.

2. Chapter 1 - Buyer-supplier relationship and resilience to supply disruptions

2.1 Foreword of Chapter 1

The first chapter of this dissertation is entitled *"Buyer-supplier relationship and resilience to supply disruptions"*, and it is a joint work with Pr. A. Chaturvedi. It explores empirically buying firms' resilience to systemic supply disruptions, and attempts to determine whether this resilience depends on several specific supply chain practices related to the buyer-supplier relationship (i.e. diversification, loyalty, contract length, communication, coordination and financial pressure).

For those supply chain practices, buying firms can manage their suppliers consistently with a close, or a weak, buyer-supplier relationship. For example, diversifying supply, which would tend to be more consistent with weaker buyer-supplier relationships, enabled *Nissan* to recover faster from supply disruptions due to the 2011 Thai floods, as the firm could switch its orders from disrupted suppliers to non-disrupted suppliers. On the contrary, when *Renesas* was hit by the Japan quake of 2011, several Japanese car makers that had concentrated their purchase with *Renesas* decided to send their own workers to fasten the recovery of their supplier. Since those examples illustrate that both supply diversification and concentration can be efficient to cope with supply chain disruptions, it is unclear whether a firm that manages supply chain practices accordingly to a weak buyer-supplier relationship would be more resilient to supply disruptions than a firm managing supply chain practices accordingly to a close buyer-supplier relationship. We tackle this issue in this project.

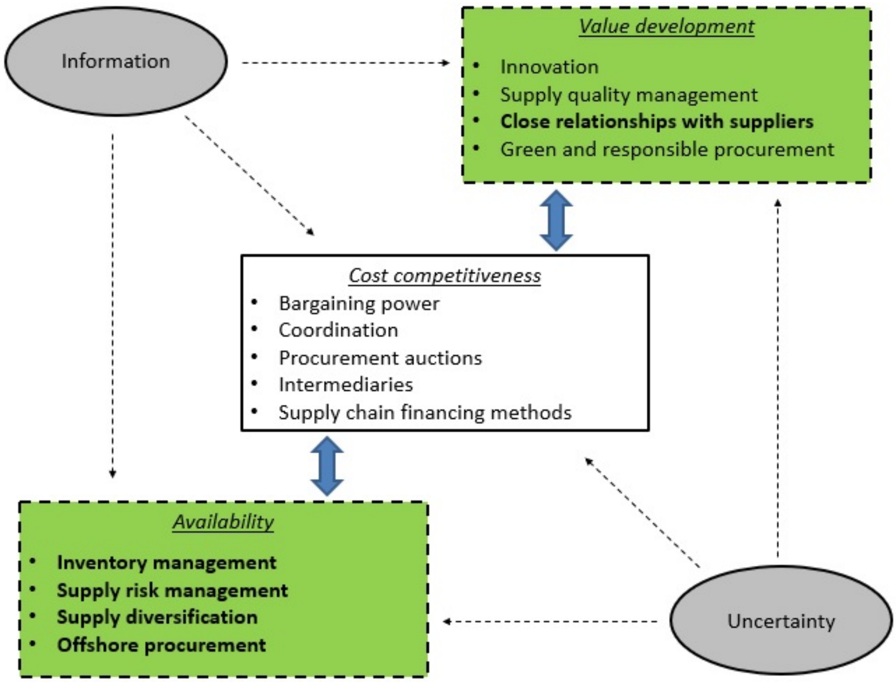

Figure 3: Positioning of Chapter 1 according to the framework presented in Figure 2.

Because this chapter deals with global supply chains resilience to systemic supply disruptions, it is directly related to the product availability procurement function through the inventory management, the supply risk management, the supply diversification and the offshore procurement levers, as illustrated on Figure 3. However, in this chapter, we attempt to explain supply chain resilience with supply chain practices related to buyer-supplier relationships. Namely, we investigate whether a lever related to value development (i.e. close relationships with suppliers) could, although it is not its prime objective, be used as a lever to improve product availability, or, on the contrary, whether it would expose the buying firm to a greater supply risk, and hence reduce its resilience to supply disruptions. We also define trade credit as an indicator of the financial pressure that a buyer puts on its suppliers, in order to study whether a buyer putting more financial pressure on its suppliers (which is associated with weaker buyer-supplier relationships) would be more (or less) resilient to supply disruptions. However, this chapter remains principally focused on product availability and value development.

Since the present business context is characterized by both a higher risk of a supply disruption (due to less control on more complex supply chains and to increased instability) and higher consequences from supply disruption (because of increased competition), examining supply chain resilience to supply disruption is a natural manner of taking this context into account. To cope with such challenging environment, it is critical for buying firms select procurement levers that would integrate risk, in addition to cost, considerations, such that they can better mitigate the impact of a supply disruption and fasten their recovery. This is what we investigate in this chapter.

More precisely, this chapter tackles the following strategic issue: should a firm favor closer or weaker buyer-supplier relationships when deciding how to manage some supply chain practices, in order to improve the resilience of its supply chain? To provide an answer to this question, we measure the impact of supply disruptions on buying firms' shareholder value, and then we analyze whether this impact depends on some specific supply chain practices. If supply disruptions significantly affect buying firms' shareholder value, and if some supply chain practices are associated with a significantly higher resilience to such disruptions, we would expect firms to incorporate supply chain resilience as a criterion when deciding their procurement strategy on those specific supply chain practices.

Buyer-supplier relationship and resilience to supply disruptions

G. Merckx • A. Chaturvedi

Global supply chains are nowadays more vulnerable than ever, and are thus extremely challenged when a systemic shocks, like a major natural disaster, occurs as it often provokes multiple supply disruptions. This work first attempts to measure, through an event study, the impact of supply disruptions following a systemic shock on affected firms' equity. Then, it analyzes whether specific supply chain practices related to the buyer-supplier relationship (i.e. *supplier diversification*, *loyalty*, *commitment*, *communication*, *coordination* and *financial pressure*) enable firms to both mitigate better supply disruptions, as well as recover faster form such disruptions. Our findings, based on a sample of 232 observations, indicate that supply disruptions have a persistent negative impact on affected firms' equity up to 3 months after the shock. More precisely, the cumulated impact of supply disruptions on firms' equity is significant over this period of time. With a subset of our complete sample, we obtain in addition that the supply chain practices related to the buyer-supplier relationship jointly explain firms' ability to mitigate supply disruptions. In particular, we find that behaving consistently with a strong buyer-supplier relationship, through putting less financial pressure on suppliers, and behaving consistently with a weak buyer-supplier relationship, through diversifying supply, having bigger inventories or having less regular contacts with suppliers, favors mitigation. On the other hand, it is less clear whether the supply chain practices influence significantly the recovery from a supply disruption.

2.2 Introduction and literature review

Over the last decades, supply chains vulnerability has increased along two dimensions. On the one hand, supply chains are more likely to face a supply disruption. Factors like globalization and outsourcing opportunities have generated longer supply chains (both in terms of number of linkages and distance between these), reducing firms' visibility and control over their own supply chain, therefore resulting in a greater risk that one of the linkages gets disrupted. This risk is moreover exacerbated by global uncertainty, which has continuously grown as unexpected events (e.g. strikes, natural disasters, terrorism...) occur at a faster rate than ever (Coleman, 2006). On the other hand, the impact following a supply disruption is likely to be higher than what it would have been in the past. The influence of the lean philosophy has led buyers to drastically limit redundant capacities and inventories, as well as to continuously reduce their supply base size, to regularly reach no more than a single source per component (Sheffi & Rice, 2005). *Ford*, for example, procures 98% of its supply from a single source (Chen and Guo, 2014). A disruption at a single linkage of the supply chain could therefore be sufficient to cause production stoppages. In 2016, Volkswagen halted production at 6 plants in Germany because one of its suppliers, *Prevent*, stopped deliveries of some iron parts and seat covers due to contracting disagreement (Riddick, 2016).

Since both the risk and the impact of supply disruptions have increased continuously in the recent years, it is not surprising that, in a survey from *PWC* (2011), supply chain executives report supply disruptions from key suppliers as the greatest risk for their supply chain. However, not only practitioners but also academicians have scrutinized supply disruption risk. Some authors have attempted to measure the negative economic impact of supply disruptions on firm performance, using either operating metrics like operating income, growth in cost, growth in inventories (Singhal, 2005a), sales growth (Singhal, 2005a; Todo *et al.*, 2015; Carvalho *et al.*, 2016), or, as we do in this project, the change in shareholder value, i.e. the stock returns (Hendricks and Singhal, 2003; Hendricks and Singhal, 2005b; Barrot and Sauvagnat, 2016; Jacobs *et al.*, 2017). Stock returns are regularly utilized to capture the economic impact of various types of events since, from the *efficient market hypothesis* (Malkiel and Fama, 1970), a firm's stock returns reflect at any moment all the relevant information about this firm. Therefore, if a supply disruption has any impact on a firm profitability, it should be incorporated in the stock returns at the time of the disruption. However, the complete effect of a disruption is typically difficult to assess immediately after the disruption (Sheffi and Rice, 2005), such that information about the impact of the disruption on buyer's operations would be updated regularly after the disruption. This is particularly true under a systemic shock, like a natural disaster, which is likely to provoke multiple simultaneous supply disruptions. The stock returns would then adapt in parallel with the information updates. Since stock returns are available on a daily basis, unlike operating metrics, they are especially convenient to quantify the effect of a supply disruption on a buyer over time, and hence to determine how resilient are those firms' to supply disruptions, with resilience being defined as *"the ability to bounce back from a disruption"* (Sheffi and Rice, 2005).

While it is intuitive that a firm's supply chain structure could influence resilience to supply disruptions, it is not trivial which supply chain practices drive resilience. Indeed, various supply chain practices can improve supply chain resilience to disruptions. The theoretical literature has largely documented the benefits for resilience of redundancy, among others through excess inventories or supply diversification (Sheffi and Rice, 2005; Chopra and Sodhi, 2004). For example, *Nissan* recovered faster from the 2011 flooding in Thailand by having diversified sources of supply (Haraguchi and Lall, 2014). However, other supply chain practices like close collaboration (Christopher and Peck, 2004) or supply chain visibility and joint problem solving (Kleindorfer and Saad, 2005) can also foster resilience, as shown by the following anecdotal evidences. Several Japanese car makers could largely limit the impact of a supply disruption, as they sent their own workers to resume operations at the chips manufacturer *Renesas*, whose factory had been devastated by the 2011 GEJE (Okazumi et al., 2015). A similar (and well-known) story had happened with *Toyota* and its p-valves sole supplier *Aisin Seiki* (Nishiguchi and Beaudet, 1998). Typically, such collaborative efforts are easier with a smaller supply base, and are thus often not complementary with supply diversification, which would be, as excess inventories, associated with weaker buyer-supplier relationships, whereas supply chain practices related to collaboration would often be associated with closer buyer-supplier relationships. It is therefore unclear which supply chain practices result in more resilient supply chains, and whether firms having more resilient supply chains exhibit closer or weaker ties with their suppliers.

In this paper, we look at two disruptive events in order to (1) measure the impact of systemic disruptive events on shareholder value (i.e. by capturing the *abnormal* returns after the events), and then to (2) explore how specific supply chain practices affect these *abnormal* returns. More precisely, we focus on the supply disruptions caused by the *Great East Japan Earthquake* (GEJE) and the flooding in Thailand, which occurred respectively in March 2011 and in October 2011. These events have been the costliest natural disasters for the past 10 years (Okazumi *et al.*, 2015), and, in addition to the tragic human losses, they caused countless situations of supply disruptions, as Japan and Thailand concentrate considerable manufacturing activities, especially in the automotive and electronics industries. Notably, Todo *et al.* (2015) report that 90% of the output loss in Japan related to the earthquake resulted from supply chain disruptions, rather than from direct impact on production facilities, and that one month after the earthquake, less than 10% of surveyed firms could operate normally because of supply shortages. Although not as well known as the GEJE, the Thai floods have also strongly affected global supply chains, notably in Asia and in the US, as firms like *Toyota*, *Honda*, *Lenovo* or yet *Acer* have reported related supply disruptions (Ten Kate and Kim, 2011). From those events, we have built a sample of 232 observation of firms that suffered from the quake (142 observations) and/or from the flooding (90 observations).

Leaning on those two natural disasters, we contribute to the literature in two ways. First, we characterize the impact that systemic shocks have on firms whose supply base suffered from those events. We do this by measuring the *abnormal* stock returns over months after the disasters through an event study. Our analysis indicates that the natural disasters can have both an immediate impact on stock returns (hereafter referred to as *initial impact*) and a persistent impact, since buying firms' stock returns would adapt in parallel with the regular information updates on the situation of the disrupted supply. Specifically, we find that buying firms have their stock returns negatively affected by suppliers' disruptions up to about 3 calendar months after the event. Over that period, the negative effect of the disruption is significant (at a 5% significance level), whereas such effect is not significant for shorter periods after the event (notably because our sample exhibits cross-correlation). In addition, we derive a measure for the speed of recovery of buying firms that have faced supply disruptions (this measure is referred hereafter to as *recovery*).

Second, we note some variability across firms in their ability to mitigate the supply disruption, as well as to recover from it, and we attempt to explain this intra-firms variability along 6 supply chain practices (hereafter referred to as practices) related to the buyer-supplier relationship, i.e. *supplier diversification*, *loyalty*, *commitment*, *communication*, *coordination* and *financial pressure*. We evaluate these 6 practices through a survey and a database, *Capital IQ*.[1] Using the 46 responses obtained from the survey, we regress the *initial impact* and the *recovery* over the 6 practices. Our findings indicate that while these practices have a significant joint effect on the mitigation of the disaster (1% significance level), it is not as clear for the recovery. In particular, we find that behaving consistently with a strong buyer-supplier relationship, through putting less financial pressure on suppliers, and behaving consistently with a weak buyer-supplier relationship, through (1) diversifying supply, (2) having bigger inventories and (3) having less regular contacts with suppliers, favors mitigation. We finally highlight heterogeneous stock markets reactions to the two natural disasters over the first calendar month following the disaster. This seems to indicate that investors have limited visibility on firms' supply chain and hence would make decisions based on subjective and incomplete beliefs.

Our paper belongs to the empirical literature on supply risk, which

[1]The first four practices are evaluated through the survey and the others from *Capital IQ*.

has already attempted to estimate the effect of supply disruptions on shareholder value. Hendricks and Singhal (2005b) find that the shareholder value is significantly and negatively affected over a 1-year horizon after a disruption. While they analyze firm-specific disruptions, we consider systemic supply disruptions that would put supply chains under an extreme pressure. Focusing on the GEJE and considering many types of firms (including insurance and nuclear firms), regardless whether they have been hit directly (i.e. their own plants are impacted) or indirectly (i.e. they face supply disruptions), Jacobs *et al.* (2017) find that although the effect is significantly negative, supply chains were quite resilient to such an extreme shock (-3.73% in stock returns after 1 month). In particular, the spillover effect of suppliers on buyers is negative and significant (sample of 74 observations) over a 21-day period after the event (-2.41%). We complement this work by gathering two heterogeneous systemic events together, from which we find that stock market reaction can differ from one particular event to the other. Moreover, unlike Jacobs *et al.* (2017), we try to determine the period of time over which firms' stock returns are affected by the events.

Other empirical papers do not only evaluate the impact of supply disruptions on buying firms' stock returns, but further study factors influencing supply chain resilience. Considering firm-specific supply chain disruptions, Hendricks and Singhal (2003) find that larger firms and firms with lower growth prospects are less affected by supply chain glitches. Barrot and Sauvagnat (2016) obtain that, when a natural disaster occurs, having at least one supplier headquartered in the state of the disaster[2] negatively affects the buyer's sales and stock returns. The effect is even higher if the disrupted supplier is a specific supplier,

[2] They focus on US disasters.

with supplier specificity depending on (1) how differentiated the supplied product is, (2) the level of R&D of the supplier and (3) whether the supplier holds patents. Whereas this paper has a similar objective than ours, both the criteria to select sample firms and the factors affecting resilience that we consider are different from theirs. We next cite some papers that also investigate supply chain resilience, but using other metrics than stock returns. Carvalho *et al.* (2016) observe how production changes (i.e. sales growth rate) of firms in the disastered area (based on the GEJE) impact the production changes of their customers outside of the damaged area. With a sample mostly composed of small firms, in contrast with our sample composed only of traded firms, they find that having suppliers in the damaged area affects negatively but not significantly the buying firm's growth rate. In a similar context, Todo *et al.* (2015) show that having more suppliers outside the damaged area reduces the time needed to resume operations normally and to reach the pre-quake sales growth level. Jain, Girotra and Netessine (2016) show that supplier concentration and buyer's loyalty to its suppliers fasten recovery. However, they consider disruption as supply-demand mismatch, and recovery as percentage of expected demand that is actually supplied, considering the disruption of the period and the spillover arising from disruptions in the previous periods. This is rather distant from our definition of a systemic disruption.

Finally, our work relates to the theoretical literature dealing with practices impacting supply chain resilience. While we discuss in Subsection 2.4.1 the literature related to the supply chain practices whose impact on resilience is studied in this paper, other supply chain practices have also been considered to tackle supply risk. Notably, Tang (2006) proposes mitigating actions (e.g. forming supply alliance networks, reducing lead time, developing recovery planning systems) to limit the impact of a supply disruption. Other options also include analyzing facilities location (Snyder and Daskin, 2005) and sharing the cost of the disruption with suppliers (Bakshi and Kleindorfer, 2009). In more specific situations, Wang *et al.* (2010) favor multi-sourcing over investing in improving supplier reliability to ensure continuity of supply under high heterogeneity of supplier reliability, whereas to cope with durable supply disruptions, Tomlin (2006) advocates in favor of the utilization of a reliable supplier rather than carrying excess inventories.

The remainder of this paper is organized as follows. In Section 2.3, we calculate the impact of the natural disasters on buying firms' stock returns, whereas in Section 2.4 we investigate how this impact can be related to the buyer-supplier relationship. We finally draw our conclusions in Section 4.8, right before the appendix.

2.3 Impact of systemic disruption on stock returns

In this section, we first detail how the sample has been built in Subsection 2.3.1, before explaining the methodology used to analyze the stock returns of the sample firms in Subsection 2.3.2. Then, in Subsection 2.3.3, we analyze and discuss the effect that the GEJE and the Thai floods have had on the sample firms' stock returns. Finally, in Subsection 2.3.4, we attempt to determine the duration of the effect of the disruptive events, but this time focusing on the reserve prices, rather than on the stock returns.

2.3.1 Sample selection

To perform a statistical analysis, we start by constituting a sample of firms that faced supply disruptions related to the *Great East Japan Earthquake* (GEJE), which occurred on the 11^{th} of March in 2011, and/or to the Thai floods of 2011 (industrial parks have been hit from the 4^{th} to the 20^{th} of October in 2011). Since an event study analyzes stock returns, we followed a systematic approach that consisted in considering all the firms traded over a period spanning from September 2010 (i.e. 6 months before the first disaster) to April 2012 (i.e. 6 months after the second disaster) on either the NASDAQ, the NYSE, the AMEX or the TSE. From these, we removed the firms without likely manufacturing activities (e.g. insurance, services or financial firms), leaving us with 1013 candidate firms to enter our sample. We then determined which of those firms suffered from supply shortages after at least one of the events, by searching on *Google* for words like *"supply disruption"*, *"shortage"*, *"production halt"*, *"idle"*, *"missing"*, *"quake"*, *"floods"*, etc... in articles from periodicals (e.g. The Wall Street Journal, Reuters, The Financial Times,...) and in the firms' quarterly and annual reports. We found 142 firms whose supply base has been hit by the GEJE and 90 for the Thai floods. Among these firms, 55 were hit by both of them, such that we have a database of 232 observations for 177 different firms. Although we suspect that many other firms have been impacted, we did not include in the database firms for which we had no tangible information supporting supply disruptions following the disasters.

2.3.2 Event study methodology

In this paper, we use the event study methodology to measure the impact of supply disruptions, either due to the quake or to the floods, on buying firms' stock returns. Event studies were initially used in finance, but have been applied for long in many other fields, such as marketing or operations management. To conduct our statistical tests, we first need, for each firm, to capture the part of the daily post-event stock returns that can be attributed to the event, i.e. the (daily) *abnormal* returns (AR). Then, the daily abnormal returns would be aggregated across firms (i.e. the *average abnormal* returns or the AAR) to determine whether the disruptive events have significant statistical effect on a particular day after the event. As discussed in the introduction, after a systemic shock, the effect of the disruption would reflect over time in the stock returns, in parallel with the information flow that would be disclosed (voluntarily or not) to the investors. In that case, the *average abnormal* returns would further be cumulated over multiple days to becomre the *cumulated average abnormal returns* ($CAAR$). Because an event study requires to be performed cautiously, we discuss in the next paragraphs several practical points related to this methodology.

First, there are two main approaches to obtain the AR. One of these calculates the AR as the difference between the observed returns of a focal firm affected by an event and the observed returns of a portfolio of firms that are similar (often in size and book-to-market ratio) to the focal firm but that did not suffer from the event. This is known as the *portfolio method*. Because for a systemic shock, many firms outside of our sample would also have suffered from the event, this approach would be likely to provide biased AR. Therefore, we only use it as a mean to support our analysis of the abnormal stock returns obtained with the other approach. This second approach derives the AR by comparing a firm's performance before and after the event. More precisely, we define the estimation window, namely a period of time before the event that is supposed to represent normal conditions, which we use to infer what should be the performance of the firm after the event if there had been no event. For this, we use the established Fama, French (1993) and Carhart (1997) model, which states that stock returns are explained by 4 factors, namely the market returns (RM), the size (SMB), the book-to-market ratio (HML) and the momentum (WML). Therefore, we regress in the estimation window each sample firm's observed stock returns R over the 4 factors (using daily data from Kenneth French's website), through the following equation:

$$R_{it} = \alpha_i + \beta_i * [RM_t - RF_t] + s_i * SMB_t + h_i * HML_t + w_i * WML_t + \epsilon_{it} + RF_t, \quad (1)$$

where subscripts i and t respectively denote firm i and day t, ϵ_{it} is the error term and RF the risk-free return. We thus obtain firm i's coefficients α_i, β_i, s_i h_i and w_i, which determine how a firm i's stock returns react to the 4 factors under normal conditions. We then use these coefficients and the 4-factor data for the period after the event (i.e. the observation window) to derive, through Equation 1 again, what should have been the returns after the event if there had been no event (i.e. the *normal returns*). Then calculating the difference between the observed returns and the normal returns after the event, we obtain the (daily) AR, which thus measures the impact of a disruptive event.

Second, we need to define the date at which each of the events occurred, in order to align both events around their respective event date. In this way, AR would not be associated with a specific date anymore, but would be recorded as the x^{th} day after the disruptive event, hence facilitating the aggregation of AR after different events. For the GEJE, this is straightforward as it occurred on March 11^{th} 2011, in the middle of a trading day, and could not have been anticipated. Regarding the Thai floods, monsoon rains resulted in a first industrial park being flooded on October 4^{th} 2011, before that other industrial parks were flooded between the 5^{th} and the 20^{th} of October. However, the first park flooded has served as a warning for investors such that stock markets could anticipate that further industrial parks might be flooded in the next days. Moreover, investors might be aware of a firm's exposure to Thailand without necessarily knowing exactly in which park are located all its suppliers, and would hence react anticipatively as soon as they find out that supply chains in Thailand are affected or threatened. As a consequence, October 4^{th} 2011 would be day from which we expect to observe a reaction of the markets resulting from the Thai floods. Because there is a significant drop on the US stock markets (not related to the Thai floods) on the 3^{rd} of October, fully compensated the day after (the aggregate effect is zero), we take the 3^{rd} of October as the first day of Thai floods.

Third, the duration of the observation window musts also be decided carefully. Indeed, because it is well acknowledged that any information is immediately reflected in the stock returns (Malkiel and Fama, 1970), event studies were initially designed to analyze AR over a very short period. However, it has been shown through longer-term event studies that some events can have persistent effects. Hendricks and Singhal (2005b) find that after a firm-specific supply disruption, the 1-year $CAAR$ are significantly negative. Following them, we might be tempted to consider such a long observation window. However, this would not be without posing a certain number of challenges (see Kothari and Warner, 1997 and 2007). Notably, long observation windows increase the risk that other macroeconomic events get incorporated in the observation window and bias the analysis (especially when the events considered are aligned in calendar-time, which is our case). Specifically, our study happens in 2011 in a volatile context, notably because of the European debt crisis, and we observe two stock market movements around 4 months after both the quake and the floods. As a consequence, we limit our analysis to 4 months after the event. Over that period, most of the firms would have resumed full operations, and the complete effect of the disruptive events on the firms' supply chain would have had evaluated and reported to the investors (if it ever is). Over the 4 months following the event, we make three measurements: (1) the *initial impact*, which we measure as the 1-month $CAAR$. This leaves some time for the market to absorb information and make a first assessment of the impact of the supply disruptions on the buying firm's supply chain; (2) the duration of the impact, which we measure as the time during which negative abnormal returns keep accumulating; and (3) the *recovery*, which is calculated as the difference between the mean AAR over the month from which negative abnormal stock returns stop to accumulate, and the mean abnormal returns over the duration of the impact (i.e. the previous measure). Thus, this third measurement depends on the previous one.

Fourth, the length of the estimation window must also be appropriately chosen. While a long estimation window might not be representative of the situation of the firm at the moment of the event, a short estimation window might be strongly influenced by the usual volatility of the stock returns. As a compromise, We have chosen a 6-calendar-month estimation window, resulting in about 120 trading days to estimate the firm-specific coefficients from Equation 1. Because the Thai floods occur only 7 months after the GEJE, the period before the floods is the aftermath of the quake, and therefore is unlikely to be representative of usual business conditions. We thus consider the same estimation window for both the events, which is the period of 6 months before the GEJE. The volatility index (VIX) suggests that, over that period, the business environment was normal since the volatility was reasonable.

Fifth, to compute statistical tests, we need to estimate the variance of the $CAAR$, which requires to take two precautions. On the one hand, systemic disruptive events are likely to provoke an increase in the post-event variance, such that measuring the variance from the estimation window might underestimate the true variance, leading to an over-rejection of the null hypothesis assuming no AR. Therefore, we calculate the variance from the event window, as suggested by Campbell *et al.* (1997). Actually, we performed our statistical analysis with both the variance calculated from the event window and from the estimation window, and our findings do not change significantly, suggesting that the difference of variance before and after the event is limited.[3] For the sake of conciseness, we present in this paper the results with the variance of the $CAAR$ obtained from the event window. On the other hand, because our sample observations are clustered in calendar-time and in industry (the events that we consider have principally disrupted automotive and electronics supply chains), our abnormal returns are likely to exhibit some cross-correlation, also resulting in underestimating the true variance. We take this into account through the procedure proposed by Kolari and Pynnönen (2010), which inflate the variance of the $CAAR$ by a factor depending on the level of cross-correlation in the sample.

2.3.3 Analysis of the stock returns

Considering the practical decisions discussed in the previous subsection, we use the 4-factor model to calculate the firms' daily AR, from which we obtain the daily AAR across firms and then the $CAAR$ when cumulating the AAR over multiple days. We then test the null hypothesis $H_0 : CAAR = 0$ against the alternative hypothesis $H_a : CAAR < 0$ through computing a Student t-statistics $t = \frac{CAAR}{\hat{\sigma}}$. This standard pro-

[3]To be even more certain of this conclusion, one might want to use a GARCH model, which would calculate the variance of the $CAAR$ as a function of the previous error terms.

cedure, described more in details notably in Campbell *et al.* (1997), enables us to analyze first the *initial impact*, namely the $CAAR$ of our complete sample after 1 calendar month (hereafter, we also use trading days, with one calendar month being equivalent to 20 trading days). We find that supply disruptions following systemic shocks result in an *initial impact* of -0.17% (i.e the average decrease in stock returns over a 20-trading-day period), which is not significantly negative. We then observe that the $CAAR$ decrease up to 3 calendar months after the disasters (see the left plot of Figure 4). At that time, the $CAAR$ are -10.36%, which is significant (at a 5% significance level). As mentioned earlier, our sample firms' AR exhibit some cross-correlation as it is clustered both in calendar-time and in industries. Since even a small amount of cross-correlation has a strong impact on statistical tests (Kolari and Pynnönen, 2010), obtaining significant abnormal returns is not straightforward, despite that we consider highly disruptive events. The left plot of Figure 4 illustrates that negative $CAAR$ are observed almost from the day of the event, up to 3 calendar months after, but the right plot shows that these negative $CAAR$ are significant only for periods of time of about 60 days after the event. With this finding, we show that systemic supply disruptions have a persistent negative impact on stock returns, which implies that a buying firm should take supply chain resilience into account when deciding its procurement strategy. In Section 2.4, we attempt to determine specifically which supply chain practices would result in a better supply chain resilience for a buying firm, in order to provide guidelines on how firms can manage their procurement strategy such that they would strengthen their resilience to potential systemic supply disruptions.

Because we consider two different events and firms traded either on

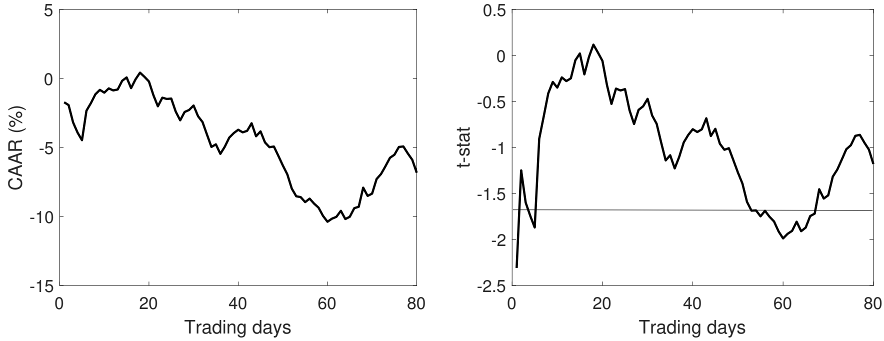

Figure 4: Behavior of our sample (left) cumulated average abnormal returns (in %) and (right) related t-statistics over trading days following the supply disruption.

US or on Japanese stock markets, our sample is actually composed of 4 subsamples, as illustrated on Figure 5. To gain deeper understanding in our results on the *initial impact*, we observe individually those subsamples. The two events actually reveal different realities. As the quake was largely advertised, we observe an immediate (over)reaction in the days following the disaster, and a correction in the days after. While this immediate reaction was negative (on average) for the Japanese firms, it was actually positive (on average) for the US firms. The investors assumed that most of the Japanese firms would be strongly affected by the quake, which would benefit their US competitors (our sample contains US and Japanese firms from similar industries). After this immediate reaction, both Japanese and US firms observe negative abnormal returns up to 60 days after the event (see Table 1 for detailed $CAAR$ of subsamples). The different immediate reactions of the stock market about US and Japanese firms confirm that considering 20 trading days for the *initial impact* is relevant. For shorter periods, the stock market reaction would probably not be representative of the ability of supply chains to mitigate

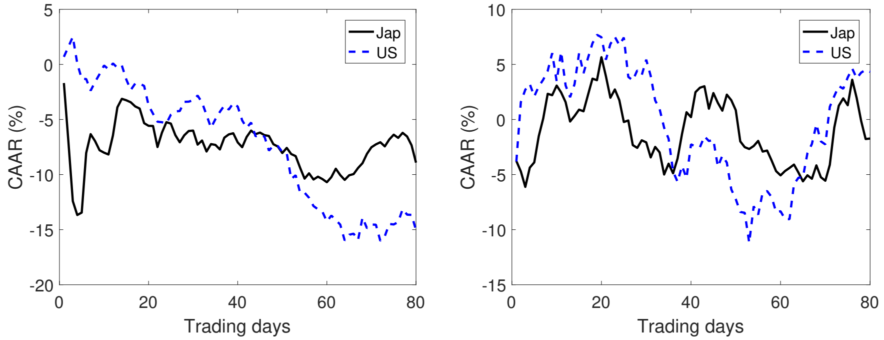

Figure 5: Behavior of our sample cumulated average abnormal returns (in %) after GEJE (left) and Thai floods (right).

	Full sample	Quake - Japan	Quake - US
1 month	-0.17%	-5.58%	-3.60%
3 months	-10.36%	-10.69%	-14.25%
	Flooding - Japan	Flooding - US	Updated sample
1 month	5.65%	7.47%	-1.45%
3 months	-5.07%	-8.33%	-11.49%

Table 1: $CAAR$ for the complete sample and for subsamples, after both 1 and 3 calendar month(s).

the effect of the systemic shock.

In contrast with the quake, the floods have not reflected immediately in the stock returns of firms whose supply base has been disrupted as can be seen on Figure 5 (right). The reason for this could be that the Thai floods have been less publicized, and thus that their impact on supply chains got absorbed by the market less rapidly. Actually, at the moment of the floods, there seems to be an increasing trend in the sample firms' stock returns, which continues up to about 20 days after the Thai floods. After this length of time, the $CAAR$ start decreasing up to about 60 days after the event, as for the quake. Figure 5 illustrates these observations.

The analysis of the *initial impact* across subsamples suggests that different natural disasters can result in heterogeneous stock market reactions. As we investigate how buying firms' stock returns vary when proper suppliers get disrupted, these firms might only be affected several days after the event if they have mitigation strategies, such as excess inventories, enabling them to keep operating normally for some days. The immediate reaction of the stock markets would thus be anticipative, and hence would not always depict accurately the current state of the supply. We advance two reasons that can justify why the stock market anticipative reaction would differ across disasters. First, because stock market reactions are often emotional, the stock returns right after the events might depend on how spectacular and publicized these are. In our case, the GEJE, which has been extremely documented, would have resulted in an over-reaction on the short-term, while the Thai floods, less covered in the press, would have resulted in an under-reaction. Because buying firms affected by supply shortages would not reveal rapidly that they face supply disruptions following an event, or might voluntarily understate the impact, an under-reaction could be corrected some time later. Second, as investors might not always be aware of the true exposure of firms to some geographic locations, their anticipation of the disruption impact on a buying firm's supply chain might be biased. For the GEJE, it was rather clear that most of the Japanese firms would be affected, whereas the extent of supply chains exposure to Thailand was less intuitive.

Next, we define our measure for *recovery* based on the previous findings. Namely, as we have shown that the complete effect of the supply disruptions is realized over 3 calendar months after the event (see the right plot of Figure 4), *recovery* is calculated as the mean AAR over the first month from which negative *AAR* stop accumulating (i.e. month 4 after the disruption), less the mean *AAR* over the 3 months right after the disruption.[4] *Recovery* therefore measures the slope of the recovery of firms that faced supply disruptions, which is positive (see Figure 4). We perform a paired samples t-test and find that the *recovery* is significantly greater than 0 (at a 1% significance level). This supports our observation that buying firms' stock returns stop being affected after, on average, a 3-month period following a systemic disruptive event. The objective of this measure is however to quantify the recovery such that we can, in the next section, study whether specific supply chain practices improve recovery after supply chain disruptions.

To support our results from the 4-factor model, we also compute the abnormal returns using the *portfolio method* as discussed earlier. As the portfolios used with this method would also include firms that have faced supply disruptions or other damages from the disasters (notably our sample firms as we use predetermined portfolios available on Kenneth French's website), this method would underestimate the magnitude of the *AR*. However, it enables to see whether stock market movements due to other macroeconomic factors than the event that we consider might explain the negative *AR* that we observe. The *portfolio method* supports the 4-factor model for all subsamples but the one with the Japanese firms having suffered from the Thai floods. According to the *portfolio method*, our subsample composed of Japanese firms affected by the thai floods has exhibited slightly greater returns than portfolio firms. Therefore, we suspect that other elements could have affected the Japanese firms that faced supply shortages after the Thai floods, and hence we do not

[4]Note that to measure the impact of the disruptive events on the firms' stock returns, it is more intuitive to use *cumulated AAR*, while to interpret the regressions, it makes more sense to use *mean AAR*.

consider these firms for the analysis of the next section. The *updated* sample (i.e. the whole sample less the Japanese firms having suffered from the floods) still has 192 observations and exhibits -1.45% of $CAAR$ after 1 month (not significant) and -11.49% after 3 months (significant). Note that the abnormal stock returns for the US firms after the GEJE with the *portfolio method* take a bit more time to decrease (around 40 days). Hence, we can not be completely certain that the decrease is not driven by other factors. However, we have seen for the Thai floods that the effect would not necessarily be felt immediately. Moreover, the competitive effect, favorable to US firms could have contributed to make the AR decreasing later. Ideally, we would thus consider a sample without the US firms having suffered from the GEJE, as it might bring noise into the regressions that we present in the next section. However, this would result in a smaller sample for the regressions, which would also be detrimental to our study. Thus we keep the *updated sample*, but also provide aside analysis for the sample with only US firms affected by the Thai floods and Japanese firms affected by the GEJE.

2.3.4 Duration of the impact of the events

To test the results that we obtain from the analysis of the abnormal returns, we perform another study of the duration of the effect of the disruptive events. Rather than focusing on stock returns, as in the previous subsections, we lean on the stock prices to observe how much time the firms facing systemic supply disruptions need to recover from the disruption. More specifically, disruptive events often have a direct negative impact on stock prices, as we observe with the $GEJE$ (see previous analysis). Thus, we calculate the time that happened between the drop in the sample firms' stock prices following an event and the moment at which the stock prices reach back their pre-event level. To cope with the day-to-day volatility of the stock prices, we measure the pre-event stock price as the mean of the last five trading days, and the post-event daily stock prices as a five-days moving average. As we know that macro events occurred four months after each event, we use this four months after the event as the upper bound of our analysis. Therefore, firms that did not recover their pre-event stock price after four months were considered as having recovered after four months.

This method confirms the heterogeneous reactions of the stock market after the $GEJE$ and the floods, since the mean number of trading days to recover is 47 for the $GEJE$ and 10 for the floods. From the stock returns analysis, we know that the impact of the floods have taken more time to materialize than the impact of the $GEJE$, and thus this duration analysis might not work correctly for the Thai floods (see the right plot of Figure 5). Therefore, our focus for this duration analysis is on the $GEJE$. As shown on Figure 6, the Japanese firms have been affected longer by the $GEJE$ than the US firms. On average, the former have needed 67 trading days (i.e. more than three calendar months) to return to their pre-event stock prices, while the latter only needed 34 days (i.e. less than two calendar months). Namely, the analysis of the duration from the stock prices suggests that Japanese firms have taken more time to fully recover from the $GEJE$ than the US firms, on average. This is intuitive as Japanese firms are likely to be more dependent upon the area directly affected by the quake than the US firms.

Analyzing the duration of the effect of the $GEJE$ from the stock returns and from the stock prices are two different analysis. When we study the stock returns, we define the recovery as the moment from which the stock returns are not lower than usual. On the other hand, when we observe the stock prices, we define the recovery as the mo-

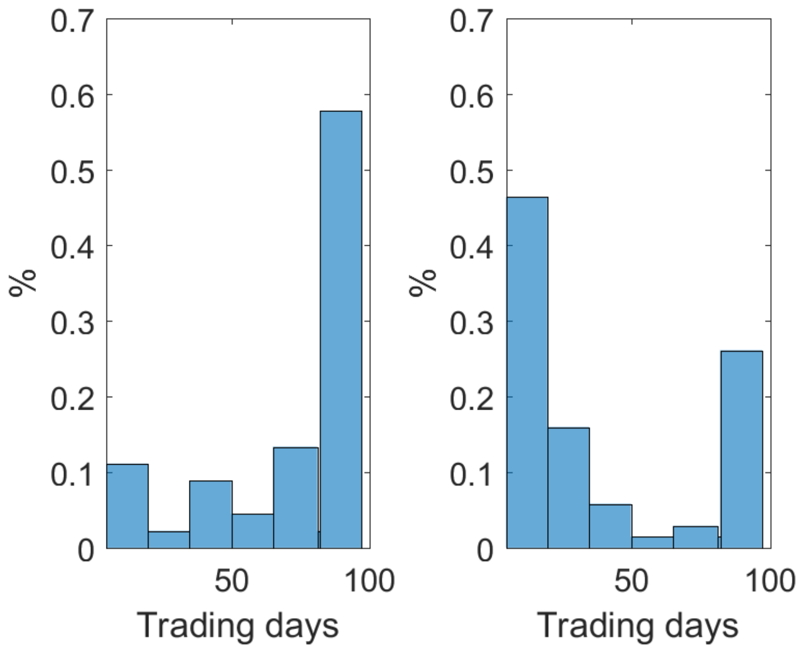

Figure 6: Number of trading days between the *GEJE* and the moment at which the firms returned to their pre-event stock prices. The left plot depicts the distribution of the Japanese firms and the right plot depicts the distribution of the US firms.

ment at which the negative impact of the quake has been totally offset. Moreover, as we have an upper bound on the duration four months after the event, our average duration from the stock prices is necessarily underestimated. Therefore, it is difficult to compare the average duration obtained from the stock prices (as well as Figure 6) with the results from the left plot of Figure 5.

2.4 Buyer-supplier relationship and resiliency

In the previous section, we have derived measures for the *initial impact* and the *recovery*. While so far we have studied those measures at an aggregated level, our second objective is to investigate whether the variability that we would observe across firms (for both measures) could be explained by specific supply chain practices related to the buyer-supplier relationship. Specifically, we attempt to determine whether managing those practices consistently with a strong or a weak buyer-supplier relationship would have a significant effect on supply chain resilience to systemic shocks. To tackle this research objective, we present in subsection 2.4.1 our hypothesis dealing with the impact of various supply chain practices on supply chain resilience. Then, we present in Subsection 2.4.2 the result from a survey sent to our sample firms, which aims at measuring how firms manage those specific practices. Leaning on this survey, we test our hypothesis through regressions in Subsection 2.4.3.

2.4.1 Hypothesis

The 6 supply chain practices related to the buyer-supplier relationship that we treat in this project are (1) *supplier diversification*, (2) *loyalty*, (3) *commitment*, (4) *communication*, (5) *coordination* and (6) *financial pressure*. Since we want to determine whether those supply chain practices affect the *initial impact* and/or the *recovery*, we provide a hypothesis about the effect of each practice on both the *initial impact* of the disruption and the *recovery*.

***Supplier diversification:* The more suppliers a buyer relies on per component, the better it mitigates the impact of a supply disruption (H1a), and the slower it recovers from a supply disruption (H1b).**

While globalization and transportation efficiency motivated firms to outsource more activities to external suppliers (Sheffi, 2001), lean management practices have led buying firms to continuously reduce their supply base size, to regularly reach no more than a single source per component (Sheffi & Rice, 2005). With a rising global uncertainty, relying on many single sources is extremely risky (Christopher and Peck, 2004, Craighead *et al.*, 2007), such that many firms are reversing and use a redundant supplier to cope with this uncertainty (Chopra and Sodhi, 2004). Since redundancy offers a shock absorber (Chongvilaivan, 2012), a buyer sourcing a component from multiple suppliers would be less affected by the disruption of one of its suppliers than if its single-source supplier is disrupted (Rice, 2003). Diversification, in addition to mitigate the impact of a disruption, might also ease recovery since inducing competition among suppliers generates investments from the suppliers to fasten the recovery to a potential disruption (Jain, Girotra and Netessine, 2016).

Although having back up suppliers dilutes the risk associated with specific suppliers, some firms voluntarily keep single-sourcing. The story with *Aisin Seiki* and *Toyota* testimonies that focusing on single sources is not necessarily detrimental in terms of resiliency, as a smaller supply base favors collaborative efforts improving resilience (Wang, Gilland and Tomlin, 2010). Indeed, a buyer single sourcing would buy greater volumes from its supplier than if it was multi sourcing, and hence has greater leverage over this supplier, notably to require managerial and technical expertise sharing from the supplier (Dowlatshahi, 1998), to cooperate in organizing the recovery (Larson and Kulchitsky, 1998) or to secure the remaining supply after a disruption (Jain, Girotra and Netessine, 2016). Finally, Christopher and Peck (2004) point out that a buyer using a single source with no short-term alternative would ascertain to be prepared to respond to a supply disruption.

On the shorter term, we expect that relying on more suppliers would limit the impact of a supply disruption, whereas having close suppliers willing to collaborate for their buyer would ease recovery on the longer term.

<u>Loyalty</u>: The longer the buyer has been working with its suppliers, the better it mitigates a supply disruption (H2a), and the faster it recovers from a supply disruption (H2b).

Buyers' loyalty to their suppliers favors resilience in two ways. On the one hand, it would make suppliers more willing to collaborate with the buyer if this faces a supply disruption. This is because long-term relationships require idiosyncratic investments, offer an advantage to the supplier (over other potential suppliers) for this particular buyer's business (Kalwani and Narayandas, 1995) and foster commitment in the relationship (Anderson and Weitz, 1989). It would thus be costlier for suppliers committed to long-term relationships with a buyer if this had to be disrupted, motivating such historic suppliers to collaborate for the buyer's rapid recovery, or to secure the remaining capacity if they are responsible for their buyer's disruption. On the other hand, loyalty results in more efficient collaboration, as long-term cooperation enables a buyer and its suppliers to develop problem-solving capabilities (Nisiguchi and Beaudet, 1998), efficiency in the information exchange (Prajogo and Olhager, 2011) and trust (Dyer and Chu, 2000; Doney and Cannon, 1997). In addition, loyalty would also improve the buyer's knowledge of its suppliers' operations and networks, an therefore the supply chain resilience (Christopher and Peck, 2004). However, Anderson and Jap (2005) point out that old relations often deteriorate and must be monitored to avoid supplier complacency. Similarly, a buyer that has been working for long with the same suppliers might be less flexible to switch frequently of suppliers and to qualify new suppliers. Todo *et al.* (2015) document that such supplier switches have been frequent after the GEJE. Considering the amount of arguments that have been raised, we expect that a buyer facing a supply disruption would both suffer less and recover faster from the disruption, if it has a longer history, on average, with its suppliers, as compared to a buyer that would have a shorter history with its suppliers.

***Commitment*: The longer the contract a buyer offers to its suppliers, the better it mitigates a supply disruption (H3a), and the faster it recovers from a supply disruption (H3b).**

Mutual commitment is a major factor for a successful buyer-supplier relationship (Krause, Handfield and Tyler, 2007), notably because it positively affects trust (Kwon and Suh, 2004). Trust, in turn, favors collaboration between partners, enabling faster recovery. Moreover, Turnbull, Oliver and Wilkinson (1992) show that long-term contracts and higher commitment from partners make them more dependent upon each other. As in hypothesis 2, this would incentivize the supplier to support its buyer facing a supply disruption. Finally, Jain, Girotra and Netessine (2016) point out that a supplier is typically willing to sacrifice some short-term benefits to cooperate with a buyer that is disrupted if it expects higher benefits on the long-term from this buyer. This would intuitively be more likely if the buyer is more engaged with the supplier, for example with a long-term contract. Therefore our hypothesis state that partners commitment would make the buyer's supply chain more resilient. Following Speckman's (1988) argument that buyers and suppliers can prove their commitment by engaging in long-term contracts together, we use contract length as a proxy for buyer and supplier commitment into the relationship.

***Communication*: The more regular the contacts between a**

buyer and its suppliers, the better it mitigates a supply disruption (H4a), and the faster it recovers from a supply disruption (H4b).

Efficient information sharing between a buyer and its supply base fosters resilience along two dimensions. First, upfront any disruption, it improves buyer's visibility on its suppliers' operations (Christopher and Peck, 2004; Speckman, 1988), providing the buyer a better knowledge about the exposure risk of its suppliers, such that it could set up adequate mitigation plans. Second, if a disruption occurs, an efficient communication between supply chain participants would enable the buyer to quickly receive, or request, information from a supplier that would be in trouble, accelerating its responsiveness (Lummus et al., 2005). The Nokia-Ericsson case illustrates that having fast, regular and complete information can be crucial in case of a supply disruption, notably to secure the remaining supply (Latour, 2001). Information sharing further helps to build trust (Doney and Cannon, 1997), which can motivate collaboration in the case of a disruption. Heide and Miner (1992) even draw a direct link even between frequent contacts and suppliers' willingness to cooperate. In absence of any valuable counter-argument, we expect buyers more frequently in contact with their suppliers to be more resilient to supply disruptions, and to recover faster from these.

<u>Coordination</u>: The higher the inventory levels, the better the buyer can mitigate a supply disruption (H5a), but the slower it recovers from a supply disruption (H5b).

To measure the coordination across partners' supply chains, we use the level of inventory as proxy, since these are often inversely correlated. For example, the lean philosophy, through its *just-in-time* dimension, is typically associated with low levels of inventory, and with a high level of coordination between the buyer and its suppliers (Levy, 1997; Zimmer, 2002), which can speed up recovery. However, low levels of inventory would expose supply chains to a greater impact in case of an unexpected supply disruption (Yu, Zeng and Zhao, 2008; Park, Hong and Roh, 2013), since it would be a buffer to mitigate disruptions (Chopra and Sodhi, 2004). As a consequence, we suppose that having more inventories (and hence less coordinated supply chains) would favor mitigation, but not recovery. We use the days inventory outstanding (i.e. the average inventory divided by the total cost of goods sold, multiplied by 365 days) from *Capital IQ* as a proxy for supply chain coordination.

***Financial pressure:* The less financial pressure a buyer puts on its suppliers, the more resilient it is to a supply disruption (H6a), and the faster it recovers from a supply disruption (H6b).**

Several authors (e.g. Kleindorfer and Saad, 2005) point out that profitability of both parts is an important factor of success of a buyer-supplier relationship. Therefore, buyers that would want to maintain a strong relationship with their suppliers would avoid putting excessive financial pressure on their suppliers. Excessive financial pressure could, in addition, result in negative consequences in case of a disruption. On the one hand, suppliers directly disrupted might face difficulties to recover as desired if they face some financial constraints. They might even be at risk for going bankrupt, as testimony the 1,698 firms that went bankrupt after the GEJE (The Japan Times, 2016). This is particularly true for small firms having a limited access to credit (Tang, Yang and Wu, 2017). This could be detrimental to the buying firm. Carvalho *et al.* (2016) show that supplier bankruptcy leads to a more negative effect than simple supplier disruption. Following this, we expect that a buyer putting less financial pressure on its suppliers would mitigate better a supply disruption. On the other hand, a supplier deriving a low benefit from its relationship with a buyer would be less willing to make efforts to help this buyer to recover. This could be either through not awarding the remaining supply to this buyer (if the supplier is directly affected), or through refusing to cooperate with the buyer to fasten its recovery. This motivates our hypothesis $H6b$.

We use the *average days accounts payable outstanding* from *Capital IQ* to estimate the financial pressure that a buyer puts on its suppliers. This measure captures the average number of days that would happen between that the buyer receives its order and eventually pays it. This delay is often contractually imposed by the buyer, despite the fact that it can negatively affect the financial situation of its suppliers, especially if these are small (Tunca and Zhu, 2017). As this measure often depends on the bargaining power of the buyer (Ng *et al.*, 1999; Klapper *et al.*, 2012), it represents a natural measure for the financial pressure that a buyer puts on its suppliers. Examples from the food industry notably, show that firms like *AB InBev* or *Heinz* request to pay their orders 120 days after having received it (Strom, 2016), tightening the financial pressure on their suppliers.

2.4.2 Information gathering and methodology

We thus have, for each of the six practices, one hypothesis for the *initial effect* and one hypothesis for the *recovery*. To test our hypothesis, we regress the *initial effect* and the *recovery*, as described in Section 2.3, over the six practices of the buyer-supplier relationship that we consider. For this, we tried to obtain a measure for our sample firms about each of the practices. While practices 5 and 6 are evaluated through data coming from *Capital IQ*, practices 1 to 4 are evaluated through a survey (available in Appendix), which is inspired by Hendricks and Ellram (1993). The survey is voluntarily short to increase the likelihood of response from the firms, and consists of one question per practices. As it was not easy to obtain responses by mail, we have called the firms directly to make a phone interview, which consisted in simply reading the questionnaire. All the respondents were people employed by the firm surveyed, who were aware of the firm's procurement policies. Since, for each firm, there could be multiple procurement policies, as there are multiple types of items, we asked the firms to reveal their information on average for all components. We assume that the averages distinguish the buyers favoring stronger relationships with their suppliers from those preferring weaker relationships. For the 4 first practices, we respectively obtained 46, 50, 49 and 49 responses over our 232 observations. As some firms have been (indirectly) hit by both disasters, it corresponds to responses obtained from 33, 36, 35 and 35 firms over our sample of 176 firms, which amounts to a per-practice response rate of about 20%. For practices 5 and 6, we have data for all of our sample firms. A summary of the responses is provided in Table 2. However, as we focus on the *updated* sample, we actually use 38, 41, 40 and 40 responses for our principal analysis. Finally, note that, using the data that we have for all the practices (i.e. 46 observations), we can perform the Belsley test, which reveals that there is no significant collinearity among the practices that we consider, such that we keep these all.

2.4.3 Results

The regressions that we conduct in this subsection enable us to derive three major types of findings: (1) whether the practices of the buyer-supplier relationship together explain buying firms' resilience (i.e. *initial*

	Nb of observations	Max	Min	Mean	Standard error
Practice 1	46	4.5	1	2.15	0.97
Practice 2	50	31	2.5	11.84	7.39
Practice 3	49	12	0	3.13	3.14
Practice 4	49	365	0	57.49	117.48
Practice 5	232	255.4	6.9	67.8	36
Practice 6	232	257.4	19.8	61.4	31.35

Table 2: Summary of the data. Practice 1 is the number of suppliers per component, practice 2 is the years of collaboration, practice 3 is the contract length (in years), practice 4 is the number of days per year during which there is a contact, practice 5 is the days inventory outstanding and practice 6 is the days accounts payable outstanding.

impact and *recovery*), through performing a $F-test$ with a null hypothesis stating that the joint effect of the 6 practices is null; (2) which of the six practices individually influence(s) resilience, through individual $t-tests$ with the null hypothesis that a specific supply chain practice has no effect; (3) for each practice that individually influences resilience, whether a buying firm behaving consistently with a weak (or a strong) buyer-supplier relationship for that practice would be more resilient.

We start by analyzing the joint effect of practices related to the buyer-supplier relationship on the *initial impact*. For this, we regress the *initial impact* over our 6 practices. We therefore use the 37 observations for which we have responses on all the practices for the *updated sample*. Consistent with Subsection 2.3.2, the *initial impact* is defined as the $CAAR$ over the first month (i.e. the 20 first trading days) after the event. The regression output is described in Figure 7. It shows that over the 20-day period after the event, our practices have a significant effect on the *initial impact* (i.e. the p-value of the $F-test$ is lower than 1%), with an adjusted R-squared of 38.1%. Looking at $CAAR$ over other period lengths shows that the p-value of the $F-test$ is significant (at least at a 5% level) from day 16 up to day 65 after the event (e.g. for day 16, this means the $CAAR$ from day 1 to day 16, and so on for the other period lengths). This is consistent with our analysis of the abnormal stock returns in Subsection 2.3.3, which shows that over the first days after the event, the stock market reaction can be driven by emotional factors and thus often underestimates or overestimates the real impact, while it sometimes even seem to not suspect any impact at all. For such short-term periods, supply chain practices do not explain the $CAAR$ after the disruptive events. From day 16 after the event, it appears that our supply chain practices significantly influence the impact of supply disruptions on buying firms. We suggest as rationale that, at that time, more information has been absorbed by the market about the disruption, which has then corrected the anticipative measures taken right after the event. We arbitrarily stop our measurement of the mitigation on day 20 (i.e. after 1 month), as it seems to capture both the short-term effect of the disruption and the mitigation of the disruption through the buyer-supplier relationship strategy. When observing the $CAAR$ over longer periods, we see that the p-value of the $F-test$ remains significant up to a bit more than 3 months (i.e. 65 days). This also supports our abnormal returns analysis that resulted in a negative and significant impact over 3 months after the event.

Regarding the effect of the individual practices on the *initial impact*, we find that, over 20 days following the event, the most significant practice (p-value $< 1\%$) is trade credit, with buyers requiring longer payment terms from their suppliers being more affected by supply disruptions. This strongly supports $H6a$ in stating that putting more financial pressure on its suppliers would be counter productive to mitigate the effect of a supply disruption. At a 5% significance level, $H5a$ is also verified

```
Linear regression model:
    y ~ 1 + x1 + x2 + x3 + x4 + x5 + x6

Estimated Coefficients:
                   Estimate       SE          tStat       pValue
                  __________    __________    ________    _________

    (Intercept)     -0.36605       0.38339    -0.95476      0.34733
    x1               0.18232      0.097157      1.8766     0.070335
    x2             0.0072995       0.01319     0.55342      0.58408
    x3             0.0041153      0.029194     0.14097      0.88884
    x4            -0.0014775    0.00076001     -1.9441     0.061319
    x5             0.0049003     0.0022618      2.1666     0.038337
    x6            -0.0072037     0.0017363     -4.1488    0.0002533


Number of observations: 37, Error degrees of freedom: 30
Root Mean Squared Error: 0.502
R-squared: 0.484,  Adjusted R-Squared 0.381
F-statistic vs. constant model: 4.69, p-value = 0.00179
```

Figure 7: Regression of the *initial impact* (y) over the 6 practices (for example, $x1$ denotes practice 1) for the *updated* sample.

```
Linear regression model:
    y ~ 1 + x1 + x2 + x3 + x4 + x5 + x6

Estimated Coefficients:
                   Estimate        SE          tStat       pValue
                  __________    __________    ________    ________

    (Intercept)      0.66068       0.41769      1.5817       0.1242
    x1              -0.11379       0.10585      -1.075      0.29093
    x2             -0.012345       0.01437    -0.85912      0.39709
    x3               0.03466      0.031806      1.0898       0.2845
    x4            -0.0011296    0.00082801     -1.3642      0.18265
    x5            -0.0002847     0.0024641    -0.11554      0.90879
    x6             0.0041193     0.0018917      2.1775     0.037437


Number of observations: 37, Error degrees of freedom: 30
Root Mean Squared Error: 0.547
R-squared: 0.288,  Adjusted R-Squared 0.146
F-statistic vs. constant model: 2.02, p-value = 0.0934
```

Figure 8: Regression of the *recovery* (y) over the 6 practices (for example, $x1$ denotes practice 1) for the *updated* sample.

suggesting that buying firms can mitigate disruptions through carrying out excess inventories. Finally, for a 10% level of significance, practices 1 and 4 are also significant, such that having a more diversified supply base per component contributes to mitigate supply disruptions, whereas having more regular contacts with its suppliers is penalizing to mitigate disruptions. While our hypothesis $H1a$ is verified, $H4a$ is reversed. This is particularly surprising as we had found no strong argument for more frequent contacts being detrimental to mitigate disruptions. A potential explanation for this is that regular communication between a buyer and its supplier would make communication less proactive in case of a disruptive event, as the disrupted firm would know that it would rapidly be in contact with its buyer. Thus, the disrupted firm would rather communicate in priority with the buyers with which it has less regular contacts. Practices 2 (loyalty) and 3 (contract length) seem to have no impact on the mitigation effect, hence $H2a$ and $H3a$ are not supported. According to those observations, buying firms favoring weaker relationships with their suppliers would foster resilience in the sense that they can mitigate supply disruptions through diversifying supply, having less frequent contacts with their suppliers and carrying out excess inventories (since these practices are typically associated with weaker buyer-supplier relationships). On the contrary, buying firms opting for closer buyer-supplier relationships would mitigate disruptions through putting less financial pressure on their suppliers (which is associated with stronger buyer-supplier relationships). These results are summarized in Figure 7. Note that, as a robustness check, we have performed all our regressions without dependent variables that we have found to be non-significant. These new regressions simply confirm all of our previous findings and are therefore not presented in this paper.

We then analyze the *recovery*, which we define as the mean AAR of month 4 after the event less the mean AAR of the 3-month period following the event. Hence, the higher the *recovery* value, the faster the buying firm has recovered. This measure is relative to how much firms have been affected by the disruptive event, and how much they have recovered from it. As the individual firms' *recovery* value itself does not represent much, we simply use it to investigate which supply chain practices could be associated with faster, or slower, recovery. Regressing the firms' individual *recovery* over the six practices leads to the following findings (see Figure 8 for the regression output). First, the p-value of the $F-test$ is significant, but only at a 10% level, making the six practices together likely to be meaningful in explaining the firms' recovery. The related adjusted R-squared is rather low: 14.6%. For the recovery, only practice 6 is significant ($< 5\%$). However, our hypothesis $H6b$ is not supported as a buyer putting more financial pressure on its suppliers would recover faster from supply disruptions. Because none of the other practices seems to have a significant impact on recovery, hypothesis $H1b$, $H2b$, $H3b$, $H4b$ and $H5b$ are also not supported.

While the results presented so far are based on the *updated* sample, we complete our analysis by computing the same regressions but on different samples (see the discussion in the last paragraph of Subsection 2.3.3). Focusing on the sample with only Japanese firms having suffered from the GEJE and US firms having suffered from the Thai floods, which is thus the sample for which the impact of the disruptions is the more obvious, the results for the *initial impact* would not differ significantly than those of the *updated* sample. The p-value of the $F-test$ ($< 0.1\%$) and the adjusted R-squared (59.6%) would even be more convincing than for the *updated* sample. The only notable difference is that practice 4 (i.e.

```
Linear regression model:
    y ~ 1 + x1 + x2 + x3 + x4 + x5 + x6

Estimated Coefficients:
                    Estimate         SE          tStat        pValue
                   __________    __________    ________    __________

    (Intercept)      -0.14048      0.48633     -0.28886       0.77618
    x1                0.28863      0.11524       2.5046      0.022733
    x2             0.00094671      0.01535     0.061673       0.95154
    x3               0.025057     0.033419      0.74978       0.46364
    x4             -0.0022501   0.00089461      -2.5152      0.022245
    x5              0.0024788    0.0023406        1.059        0.3044
    x6             -0.0089985    0.0019848      -4.5338    0.00029374


Number of observations: 24, Error degrees of freedom: 17
Root Mean Squared Error: 0.418
R-squared: 0.701,  Adjusted R-Squared 0.596
F-statistic vs. constant model: 6.65, p-value = 0.000932
```

Figure 9: Regression of the *initial impact* (y) over the 6 practices (for example, $x1$ denotes practice 1) for the *updated* sample less the US firms having suffered from the GEJE.

```
Linear regression model:
    y ~ 1 + x1 + x2 + x3 + x4 + x5 + x6

Estimated Coefficients:
                     Estimate          SE         tStat       pValue
                   ___________    _________    ________    ________

    (Intercept)        0.50633      0.69565     0.72785     0.47661
    x1               -0.024281      0.16484     -0.1473     0.88463
    x2              -0.0090029     0.021958    -0.41001     0.68692
    x3                0.047544     0.047804     0.99456     0.33389
    x4             -0.00085998    0.0012797    -0.67203     0.51059
    x5              -0.0016993    0.0033481    -0.50755     0.61829
    x6               0.0060627    0.0028391      2.1355    0.047571


Number of observations: 24, Error degrees of freedom: 17
Root Mean Squared Error: 0.597
R-squared: 0.299,  Adjusted R-Squared 0.0521
F-statistic vs. constant model: 1.21, p-value = 0.348
```

Figure 10: Regression of the *recovery* (y) over the 6 practices (for example, $x1$ denotes practice 1) for the *updated* sample less the US firms having suffered from the GEJE.

communication) is now not significant anymore. For the *recovery*, considering this smaller sample would result in a lower adjusted R-squared and in a non-significant impact. We present the regression outputs for those samples in Figures 9 and 10. For the sake of completeness, we also provide the output regressions for the complete sample (hence adding Japanese firms having suffered from the Thai floods to the *updated* sample) in Figures 11 and 12. Adding these seems to bring noise into our analysis. For the *initial impact*, the lower adjusted R-squared (29.2%) tends to confirm that the Japanese firms having been disrupted by the Thai floods might have had their stock returns after the Thai floods also influenced by another factor. However, it also supports that supply chain practices related to the buyer-supplier relationship significantly affect resilience, and especially through practice 6 (i.e. trade credit). It also tends to confirm that the practices considered in our work weakly influence recovery, as testimony the p-value of the $F-test$ (14.4%) and the adjusted R-squared (8.87%).

2.5 Conclusion

The global uncertainty threatening supply chains that are more vulnerable than they were in the past has motivated us to investigate supply chains resilience to supply disruptions. Recent natural disasters have especially emphasized the weaknesses of supply chains having supply networks concentrated in specific geographical locations, since in that case, multiple supply disruptions are likely to appear.

In this project, we wanted to quantify the impact for buying firms of such disruptions due to systemic shocks. For this, we have used affected firms' stock returns, as these should incorporate any important information, including those related to the supply issues arising from

```
Linear regression model:
    y ~ 1 + x1 + x2 + x3 + x4 + x5 + x6

Estimated Coefficients:
                    Estimate        SE          tStat       pValue
                   __________    _________    _______    __________

    (Intercept)      -0.02819     0.074654    -0.3776       0.70783
    x1                0.02493     0.018495     1.3479       0.18567
    x2              0.0018725     0.002418     0.7744       0.44348
    x3               0.000795    0.0060982    0.13036       0.89697
    x4            -0.00027789   0.00014297    -1.9437      0.059359
    x5             0.00085862   0.00044486     1.9301      0.061084
    x6             -0.0014249   0.00036315    -3.9238    0.00035378


Number of observations: 45, Error degrees of freedom: 38
Root Mean Squared Error: 0.107
R-squared: 0.389,  Adjusted R-Squared 0.292
F-statistic vs. constant model: 4.03, p-value = 0.00321
```

Figure 11: Regression of the *initial impact* (y) over the 6 practices (for example, $x1$ denotes practice 1) for the complete sample.

```
Linear regression model:
    y ~ 1 + x1 + x2 + x3 + x4 + x5 + x6

Estimated Coefficients:
                    Estimate         SE          tStat       pValue
                   ___________    __________    ________    ________

    (Intercept)        0.49286       0.38629      1.2759     0.20974
    x1               -0.048924      0.095701    -0.51122     0.61215
    x2               -0.015971      0.012511     -1.2765     0.20952
    x3                0.033426      0.031554      1.0593     0.29615
    x4             -0.00072456    0.00073977    -0.97944     0.33356
    x5              7.5492e-05     0.0023019    0.032796     0.97401
    x6                0.003729     0.0018791      1.9845    0.054456


Number of observations: 45, Error degrees of freedom: 38
Root Mean Squared Error: 0.551
R-squared: 0.213,  Adjusted R-Squared 0.0887
F-statistic vs. constant model: 1.71, p-value = 0.144
```

Figure 12: Regression of the *recovery* (y) over the 6 practices (for example, $x1$ denotes practice 1) for the complete sample.

systemic shocks. We found that this impact is, as expected, negative, and takes around 3 months to be fully reflected in the stock returns. This could be either because firms have mitigation strategies (e.g. excess inventories) allowing them to maintain production levels for some time, or because the information dealing with the impact of the shock on a firm supply chain might not be estimated correctly after the event. This last argument suggests that firms have incentives to remain rather vague on how their supply chain is organized, and especially on how their supply chain is dependent upon a specific location.

Since systemic supply disruptions have a significant negative influence on buying firms' financial health, these should be interested in limiting this negative influence. In this paper, we have investigated the role that six specific supply chain practices might play in reducing the impact of systemic supply disruptions on buying firms' stock returns. Specifically, we have observed whether those six practices would influence both the mitigation of the disruption, as well as the ability to recover from the disruption. Our findings indicate that those six supply chain practices significantly explain firms' ability to mitigate supply disruptions, while it is less clear whether they explain firms' recovery. This result suggests that firms desiring to incorporate supply chain resilience in their procurement strategy decisions should rather focus on supply chain practices improving the mitigation of a disruption, since it is not clear whether different supply chain practices result in a better ability to recover. We observe that for most of the practices with a significant impact, firms favoring weaker buyer-supplier relationships with their suppliers mitigate better supply disruptions. In particular, diversifying supply, non-regular communication with suppliers and carrying out excess inventories are supply chain practices enabling firms to be more resilient to supply disruptions on the short-term. However, putting less financial pressure on suppliers also allow buying firms to improve their resilience to supply chain disruptions, despite that it is consistent with close buyer-supplier relationship.

Aside the practical points discussed in Subsection 2.3.2, we highlight in this last paragraph two limitations of this work. (1) The first limitation is the small sample size for the regression analysis of Section 2.4. Sample size is often the bottleneck in studies requiring non-public data from (traded) firms. Although the sample size is taken into account in the statistical analysis, it obliges us to remain cautious in generalizing our conclusions. (2) Also, the reduced time window between both the events, coupled with the fact that some firms have been affected by both natural disasters could introduce some bias in our results. Indeed, a firm having suffered from supply disruptions related to the quake might not have completely recovered when facing similar disruptions following the Thai floods. On the contrary, some might also argue that such firms would have learned lessons from the first systemic shock, and would thus be better prepared for the second shock. Those two limitations directly provide avenues for future research, which could enable to draw more general conclusions.

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Appendix

Supply Chain Survey

We investigate the impact of the buyer-supplier relationship on the resilience of a firm to an unexpected event that disrupts the buyer's supply. We wonder whether buyers that have close ties with their suppliers recover faster from a supply disruption, as compared to buyers that have weaker ties with their suppliers.

We have selected an important number of firms and your company is one of these. Therefore we would be thankful if you would agree to answer this short questionnaire.

Some instructions and information:

1. **Responding should not take more than 5 minutes.**
2. **Your answers will be strictly confidential and aggregated with other answers, such that the name of your company will not appear anywhere.**
3. **If you are not sure about an answer, please provide your best estimate. An answer does not need to be exact to be helpful.**
4. **Feel free to comment any answer (in the same box).**
5. **We would be pleased to provide you with a copy of our results. You can ask for it at the end of the questionnaire**

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I will answer the following questions as if we were in... (If possible, answer the questions as if we were in 2010 - before the quake and the floods)

☐ 2010

☐ 2014, I do not remember how things were in 2010

☐ 2014, but the procurement policies did not change much since 2010

Questions

1) In general, how many suppliers does your company have **per component**?
……………………………………………………………..
2) On average, for how long has your company been doing business with its actual suppliers?
……………………………………………..
3) On average, what is the contract length that your company offers to its suppliers?
……………………………………………..
4) When there is no particular event/issue, how often on average does your company have contacts with a component supplier's manager? ………………………………………………….
5) Which company are you working for? ....

6) Are you interested in receiving the conclusions of this research project once finished?

☐ Yes

☐ No

In order to avoid validating false responses (and to eventually receive a copy of our results), please leave a valid e-mail address. This will only be kept for the purpose of this study.

……………………………………………………………………………………………..

Thank you very much for your participation!

3. Chapter 2 - Contract length and supplier investment

3.1 Foreword of Chapter 2

The second chapter of this dissertation is entitled *"Short vs. long-term procurement contracts when supplier can invest in cost reduction"*, and it is a joint work with Pr. A. Chaturvedi. In this chapter, we use an analytical model based on auction theory, as a mean to investigate how the length of contract(s) auctioned off by a buyer affects its procurement expenses, when the winning supplier can invest in improving its future production cost. This situation creates a trade-off for the buyer between motivating supplier effort through a long-term contract and leveraging competition through shorter-term contracts.

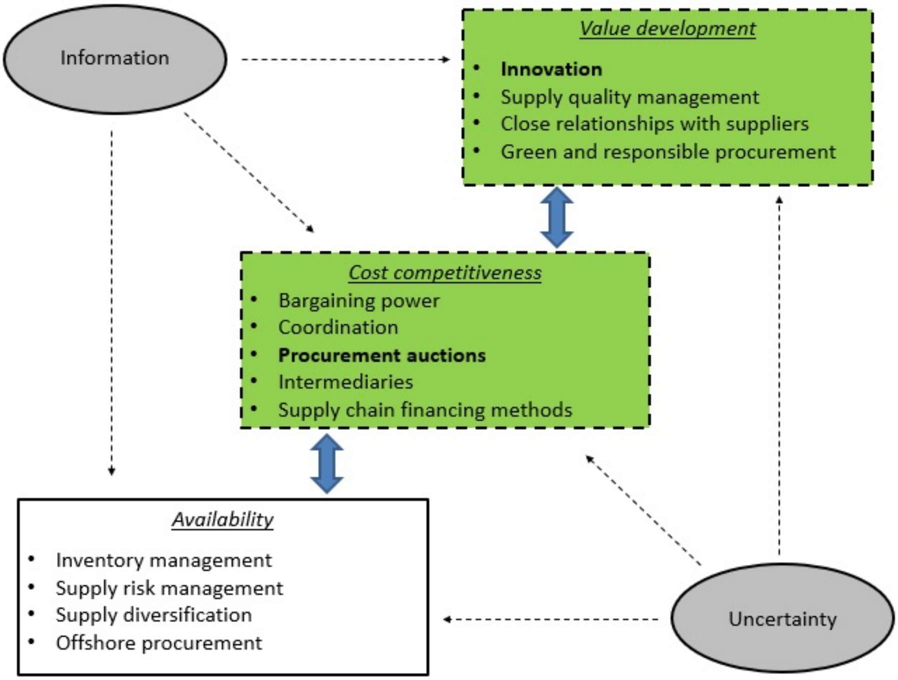

Figure 13: Positioning of Chapter 2 according to the framework presented in Figure 2.

This chapter attempts to balance the costs savings arising from suppliers' competition and from supplier's investments in process improvements. Therefore, it is directly focused on reducing procurement expenses. However, this project also investigates how to manage the uncertainty related to suppliers' adaptability to new technologies. Through this dimension, it is related to the innovation process, and thus to the value development function of procurement. The impact of uncertainty and information on this project is also significant. Namely, in our model the buyer does not know how well its different suppliers have adapted to the new technology, and uses auctions to obtain this information, as these are a mean to discover hidden information. While a long-term contract might be perceived as a greater commitment from the buyer into the relationship with the selected supplier, the focus of this work is not on the collaborative benefits that might arise from a closer collaboration between a buyer and its supplier. Hence, this chapter is only related to the cost reduction and to the value development procurement functions. Especially, it is interested in examining how to select the right auction mechanism (between auctioning a long-term contract or two short-term contracts) resulting in the highest procurement cost savings. This is summarized in Figure 13.

Globalization and better transportation technologies have given buying firms access to multiple suppliers for any component, hence increasing suppliers competition. Procurement auctions, by using available information technologies, enable the buying firms to leverage this competition and hence reduce their production cost. Unlike Chapter 1, this chapter does not use procurement levers to cope with threats arising from the environment, but rather takes advantage (through auctions) of the opportunities brought by the current environment.

The strategic dimension of this chapter is straightforward. Namely, in this project, the buyer has to anticipate suppliers' behavior, in order to chose between giving up some benefits that would be obtained through maximizing the competition across suppliers, and inflating the cost savings following supplier's investments in cost-reducing activities.

Short vs. Long-Term Procurement Contracts when Supplier can Invest in Cost Reduction

Gilles Merckx • Aadhaar Chaturvedi

In dynamic markets where cost of components changes fast, buyers typically auction off regular short-term contracts to fully leverage supplier competition in each period to continuously source from the lowest-cost supplier. However, too much competition through short-term contracts does not incentivize the incumbent supplier to make idiosyncratic investments in cost-reducing process improvement, as future business is not assured. We investigate this trade-off, between leveraging supplier competition in each period versus incentivizing incumbent's investment, with a stylized two-period model in which the buyer decides whether to auction off short-term contracts in each period or auction off a single long-term contract spanning both periods. In both cases, we characterize the optimal incumbent supplier's investment, the suppliers' equilibrium bidding strategy and the buyer's expected cost. Our analysis shows that the supplier always invests more in a long-term contract. However the buyer's cost depends on supply base size: it prefers short-term contracts for large supply base size, otherwise it prefers long-term contract. Moreover, we find that system cost is typically lower with short-term contracts and that the suppliers are always better off with short-term contracts. Finally, adding non-discriminatory or discriminatory reserve prices to our model does not fundamentally modify the trade-off, but we find that auctions with discriminatory reserve price are better at balancing this trade-off compared to long or short-term contracts.

Keywords: Contract Length; Supplier Improvement; Auctions; Supply Base Size

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3.2 Introduction

Procurement managers frequently use electronic reverse auctions to source standardized and well specified items like memory circuits, printed circuit boards, power chords and cable connectors. In dynamic markets, like consumer electronics, that see frequent evolution of technology, suppliers' cost of producing these items can change from period to period. For instance, plant level investments in either new production technology or even worker training, made either by the supplier or its sub-supplier, can have uncertain impact on a supplier's cost from one period to the next (see Carillo and Gaimon, 2004). Other factors like supply-demand dynamics could impact a supplier's opportunity cost of dedicating its capacity to any particular buyer in uncertain ways (because another buyer might value production with supplier's new technology more or less), which make it difficult to predict which supplier might offer the best price, period-to-period, to a buyer. In order to discover the current best market price, among all the potential suppliers whose cost might change from one period to the next, procurement managers often organize reverse auctions *periodically* (see Carbone 2004).

On the other hand, by assuring long-term business to a supplier, a buyer can gain cost savings from supplier's investment (in form of time, effort and resources that a supplier incurs) in reducing the production cost for this specific buyer. In this paper, we focus on supplier's investments aiming at lowering buyer-specific production cost that would be contingent upon the production experience accumulated by the supplier with this specific buyer. Namely, we consider investments that are dedicated to a specific buyer and that can not be replicated by other potential suppliers (as investments would depend on production experience). We provide three different examples of investments falling into this category. (1) For instance, some large buyers (e.g. *Ikea* or *Walmart*) have their own energy efficiency assessment programs in order to determine which investments their suppliers could realize to improve their energy efficiency and thus reduce their production cost. As a consequence, those investments made by the suppliers would be buyer specific and would not be accessible to suppliers that would not be producing for the buyer (Nguyen, Donohue and Mehrotra, 2018). (2) Other buyer-specific investments aiming at lowering production cost also include investments that the supplier would make to integrate its operations to the buyer's supply chain. Specifically, buyers often require their suppliers to align with their own IT system, despite the fact that it would initially be expensive and time-consuming for the supplier.[5] However, those investments can be necessary, notably if the buyer uses a just-in-time production system (Bensaou and Anderson, 1999). A better integration can further be achieved through investments in human capital (e.g. manufacturing engineers developing knowledge about the buyer), in manufacturing equipment or in plants or warehouses investments dedicated to a specific buyer (Dyer and Ouchi, 1993), notably to lower future inventory and transportation expenses (Williamson, 1983). (3) Buyer-specific production cost reduction could finally occur due to supplier's production learning — which requires not only sufficient production volume but also engineering trials that use expensive production capacity at supplier's end (along with employee time and effort) for controlled experiments in

[5] see Boyson, Corsi and Verbraeck (2003) for examples from the automotive and electronics industries

optimizing production processes specific to the buyer's order fulfillment (see Terwiesch and Bohn, 2001). Indeed, learning through production experience leads to cost reductions (Lewis and Yildirim, 2002), but those cost reductions actually often require parallel investments and improvements to exploit this potential for cost reductions (Dutton and Thomas, 1984).

The level of these *idiosyncratic investments* in production process improvement depends on the continuity of business that the supplier anticipates from the buyer:[6] intuitively, higher levels of idiosyncratic investment made by a supplier are riskier in short-term contracts (compared to long-term contract) since it has to compete again for buyer's business in a market where cost of suppliers can change from one period to the next. Thus a buyer can better incentivize its supplier towards making higher idiosyncratic investments by offering a longer-term contract to the supplier which in turn can benefit the buyer from the cost advantages that the supplier can offer the buyer.

Thus there exists a trade-off in buyer's sourcing strategy: it can either gain higher cost savings derived from the buyer specific, idiosyncratic, investments made by the supplier by assuring long-term contracts to suppliers or it can fully leverage supplier competition in each period by only offering short-term contracts.

To capture this trade-off we present a stylized 2-period model in which symmetric suppliers independently draw fresh costs in both the periods (to reflect the changes in suppliers' cost from periodic investments in new technology). The buyer has two sourcing options: (1) it

[6]We refer to supplier's investment in production process improvement as idiosyncratic investments since they are made for improving buyer specific production processes.

can organize a second-price auction at the beginning of each period and give a short-term contract, spanning a single period, to the lowest bidder in each period, or (2) it can organize a single second-price auction at the beginning of the first period and give a long-term contract, spanning both the periods, to the lowest bidder. To capture idiosyncratic investments made by the supplier that has won the first-period auction (from now on the incumbent supplier, in contrast with a first-period auction loser that we define as a non-incumbent supplier), the model assumes that the incumbent supplier (in either the single or the two-auction setting) can invest in process improvement which stochastically reduces the supplier's second-period cost. The level of investment made by supplier in either auction setting is a decision variable.

Intuitively, risk of losing buyer's business soon (in a short-term contract) would disincentivize supplier from making idiosyncratic investments. For similar reason, greater competition would increase the risk of investment in short-term contract. In fact we find that the difference in investments between the long and the short-term contract is increasing with the supply base size. However, with greater supply base size the buyer increases its chances of drawing a lower cost in both the periods through short-term contracts as compared to long-term contracts. Thus the buyer's decision on long or short-term contracts critically depends on its supply base size.

To quantitatively compare the long-versus-short term sourcing strategies, we next investigate buyer's cost in both the auction settings. For this, we characterize the equilibrium bids that suppliers would submit in both the auction settings. Since the incumbent supplier can invest in process improvement, hence the equilibrium bids must take into account the cost of investment and the resulting cost improvements that the suppliers would gain. We find that typically the buyer would prefer short-term contracts for large supply base size and would prefer long-term contract for smaller supply base size. However, the buyer's preference for long-term or short-term contract has a more nuanced dependence on the supply base size. This is because in a two-period setting, the investment in short-term contracts drops to zero beyond a certain supply base size, at which point the long-term contract can become more preferable for the buyer. Moreover we show that suppliers are always better off, in expectation, by participating in auctions that give away short-term contracts. Finally we find that the system cost (i.e., the sum of production cost and investment) is lower with short-term contracts than with longer-term contracts.

We also numerically investigate how our findings are affected when the buyer can optimally set non-discriminatory, and discriminatory, reserve prices to lower its procurement cost (for instance when the buyer has access to an inexpensive outside option). Neither non-discriminatory reserve prices, nor discriminatory reserve prices change the fundamental trade-off between leveraging period-to-period supplier competition versus incentivizing incumbent supplier's process improvement investment. However, we find that discriminatory reserve prices are a better tool for balancing this trade-off in comparison to short or long-term contract. More specifically, with discriminatory reserve prices the buyer can organize an auction in each period and thus leverage period-to-period supplier competition, as in the short-term contracts case, but at the same time it can discriminate in favor of the incumbent supplier in the second auction to incentivize a high investment from the incumbent, as in the long-term contract case. We find that a contract with optimally set discriminatory reserve prices always performs better than both the long-term and the short-term contract cases. We further find that buyer's expected cost in the contract with discriminatory reserve prices are closer to those in a long-term contract when supply base size is smaller, and are closer to those in short-term contracts when supply base size is bigger, consistent with our previous findings. However, with discriminatory reserve prices the buyer has sufficient control over its cost as a result of which its expected cost decrease monotonically in the supply base size.

The rest of this paper is organized as follows: we first review the procurement auctions literature in §3.3. Then we introduce the model in §3.4 and determine supplier optimal investment in §3.5. Next, in §3.6 we characterize and compare the buyer's expected cost, suppliers' surplus and system cost in both the settings. Finally we discuss the impact of reserve prices on our model in §3.7, and we present the conclusion in §3.8. All the proofs are presented in the Appendix.

3.3 Literature Review

Our work relates to the literature in procurement auctions that investigates supplier investment. Some papers completely focus on the supplier investment decision, observing how it is affected by specific factors, like the auction format (Arozamena & Cantillon, 2004) or the commitment to a mechanism (Dasgupta, 1990; Piccione & Tan, 1996). Unlike these papers, our objective is not to observe what affects supplier investment levels, but rather to determine the influence that the supplier investment opportunity has on the buyer's contract length decision and expected cost.

However, other papers also consider supplier investment as a parameter in the design of a procurement mechanism. In two different settings, Li (2013) and Gong, Li and McAfee (2012) find that the effort that a supplier exerts is tied to the amount of business that it expects from the buyer. Namely, supplier effort is maximal in sole-sourcing, whereas dual-sourcing motivates investment from both suppliers. This is consistent with our finding that a supplier invests more in long-term than short-term contracts, even if we consider idiosyncratic investments, where only the incumbent supplier can invest. Li (2013) and Gong *et al.* (2012) then balance the savings from supplier effort with those from competition, which are greater when the suppliers are more symmetric, to determine how to split the contract among two suppliers. While we too investigate how the buyer can optimize the joint benefits from supplier effort and competition, our focus is on the length rather than on the split of the contract(s). Lewis and Yildirim (2002) analyze a trade-off similar to the two previous papers, but consider learning economies rather than supplier investment. Unlike these papers, which assume at most two suppliers, we also analyze how larger supply base sizes impact supplier investment and buyer's contract length decision.

Cisternas and Figueroa (2015) design an optimal mechanism in a two-auction setting when supplier investment is observable. They find that the buyer can stimulate competition in the first period by giving an advantage to the first-period winner in the second period. Bag (1997) also states that discrimination can benefit the buyer by motivating a greater investment from the favored supplier. Their findings are in line with the results from our discussion section (§3.7), even though none of them consider differentiated reserve prices. Moreover, our focus is on the impact of contract length on supplier investments, which is not investigated in these papers.

Existing literature on contract length in the context of auctions includes Li and Debo who study two dynamic situations in which the buyer has to choose, as in our paper, between committing to a short-term or a long-term relationship. Similar to us, Li and Debo measure the benefits from opening the competition in the second period. They compare these with exogenous costs of switching of supplier after the first period, in presence of supplier learning, demand uncertainty and supplier cost of capacity (2009a), or of transferable capacity (2009b). Rather, we trade off the benefits from competition with the cost induced by a lower investment endogenously decided by the supplier that does not receive a long-term contract. Moreover, we consider a general size of the supply base (rather than two suppliers in Li and Debo (2009a)), to gauge the impact that supply base size would have on investment and on the buyer's contract length decision.

Elmaghraby and Oh (2004) study the efficiency of an eroding price contract when suppliers benefit from learning-by-doing. They show that such a contract is better than sequential auctions only if past production and switching costs give a strong comparative advantage to the contracted supplier. Similar to this work, we balance the effects of supplier cost improvement and competition. However, we focus on the impact of supply base size and contract length on the investment that the winning supplier can make to reduce its production cost, rather than exogenously fixing cost improvement through learning-by-doing (as in Elmaghraby and Oh (2004)).

Finally, our work relates to the literature that investigates the impact of supply base size on the buyer's expected cost. Counter intuitively, we find, in our work, that increasing competition does not always reduce the buyer's cost, as it can deter supplier investment. Other papers have shown that this also holds true when there is a cost of entry (McAfee &

McMillan, 1987) or a cost of maintaining the supply base (Chaturvedi, Martínez-de-Albéniz & Beil, 2014). Li and Wan (2015) investigate how supply base size affects supplier investment and competition. While we consider in our paper any supply base size of at least two suppliers, they compare situations where either the supplier is assured of the contract, or two suppliers compete for it. In conditions rather similar to our setting, they also find that having two suppliers competing, rather than one, reduces supplier investment. However, when the buyer does not (or partially) commit(s) to a mechanism before supplier effort, they first find that two symmetric suppliers could end up making divergent investments, as equal investments would be costly but would not give a cost advantage to any of the suppliers. This never happens in our model, as only the incumbent supplier actually invests, and in consequence obtains a cost advantage over the other supplier(s) for the second auction. Second, they find that a supply base size of two, rather than one, can result in higher supplier effort, since competition can motivate an extra effort from a supplier that wants to maximize its chance of winning the contract. In our paper, the suppliers compete in both settings, and therefore always make efforts. Their effort is associated with the risk of not winning the second auction, and thus decreases in the supply base size. For the same reason, investment is greater in the single-auction setting than in the two-auction setting. Lastly, Aral, Bakos & Brynjolfsson (2017) study, as we do, the interactions between supply base size and relationship-specific investments, and they also find that less competition favors larger investments. However, their focus is on the impact of information technology on these interactions under a multi-period setting, whereas our main objective is to examine the effect of contract length on both the buyer's supply base size decision and suppliers' investments. Two other major differences can be highlighted between their paper and ours: (1) they consider the effect of trust, arising from repeated interactions with the same supplier, on investments level, and (2) they use incomplete contracts (rather than second-price auctions in our case).

3.4 Model

We consider a 2-period model in which a buyer needs to procure one unit of homogeneous good in each period. Without any loss of generality, we normalize the buyer's demand to one unit per period. The buyer has n qualified risk-neutral suppliers present in its supply base in both periods. We denote by $\mathbf{c^f} = (c_1^f, \ldots, c_n^f)$ and $\mathbf{c^s} = (c_1^s, \ldots, c_n^s)$ the vectors of suppliers' per-unit cost in the first and the second period respectively. The cost of each supplier in any given period is its private information. The period-1 cost of suppliers is distributed according to c.d.f. $F(c)$ defined in the interval $[\underline{c}, \bar{c}]$ and this distribution is known to all the suppliers and the buyer. We assume that in the first period each supplier is uncertain about its period-2 cost. This reflects the fact that in dynamic markets, technology evolves fast such that suppliers cannot anticipate how well they will adapt to the new technology, hence resulting in their future cost being highly uncertain. For example, frequent plant level investments made by suppliers (or their sub-suppliers) in new production technology or worker training can have uncertain impact on their cost of producing for the buyer (see Carillo and Gaimon, 2004). For instance, uncertain yield resulting from working with new technology or uncertainty in worker skill level can result in uncertain impact of adapting technology or of a worker training program on the production cost of a supplier. Moreover, changing supply-demand dynamics in the supply chain could alter a supplier's opportunity cost of dedicating its capacity to a particular buyer, e.g., in instances when another buyer might value production with supplier's new production technology more (or an existing buyer abandons the supplier) thus increasing (decreasing) supplier's opportunity cost of dedicating the capacity for a particular buyer. Therefore in the first period suppliers are only informed about the distribution of their period-2 cost. We assume that period-2 cost of suppliers are also distributed according to c.d.f. $F(c)$ defined in the interval $[\underline{c}, \bar{c}]$ and are independent of period-1 cost. Period-1 and period-2 cost distributions are identical to reflect that the market characteristics shaping period-1 cost distribution should also shape period-2 cost distribution. Note that what matters is the relative difference between the suppliers' cost and it is the distribution of these relative differences that is identical and independent across periods.

Actually, our model is simplified in the sense that most of the time, suppliers' cost would not be completely independent from one period to the other, even if the technology is evolving fast. There could be certain components of cost that are similar across suppliers, which might be correlated across periods. Such cost components can easily be included in the analysis, but as these would not affect our findings, they are not inserted in the paper for simplicity.[7] Finally, the cost distribution is common knowledge, i.e., it is known to the buyer and all the suppliers.

In this paper we consider three different strategies that the buyer can use to procure its demand in each period. In all three strategies the buyer uses the second-price auction format, in which the buyer procures from the lowest bidder and pays it the bid quoted by the second-lowest

[7]For example, supplier i's first and second-period costs could be respectively expressed as $c_p^f + c_i^f$ and as $c_p^s + c_i^s$, where c_i^f and c_i^s would represent supplier i's types, drawn independently in each period, and c_p^f and c_p^s would represent the cost terms that are common for all suppliers in period-1 and period-2 respectively. These common cost terms could represent cost of commodities that change (and could be correlated) from one period to the next, for instance.

bidder. The first strategy of the buyer is to organize a second-price auction at the beginning of each period, and thus procure one unit from the lowest bidder of each period. Thus this two-auction case is analogous to the buyer using short-term procurement contracts to fully leverage supplier competition in each period. The second strategy of the buyer is to organize a single second-price auction only at the beginning of the first period, thus committing to procure two units from the lowest bidder of the first period. Thus this single-auction case is analogous to the buyer using long-term procurement contract to incentivize its chosen supplier to invest in process improvement. Finally, in the third strategy, which is a hybrid of the first two, the buyer organizes a second-price auction in both the periods but in the second-period auction it discriminates in favor of the incumbent supplier (who won the first-period auction) by setting appropriate reserve prices. Thus this hybrid strategy tries to optimally balance both the benefits of leveraging supplier competition in each period as well as incentivizing the incumbent supplier to invest in process improvement. We assume that for the single-auction case, the buyer can credibly commit to buy from the winning supplier the second unit of its demand (corresponding to the second-period demand of the buyer), irrespective of the incumbent supplier's cost draw in the second period. Vice-versa, we also assume that the incumbent supplier commits to supply the second unit of buyer's demand, irrespective of the supplier's cost draw in the second period. One way to ensure such commitments is through legally binding contracts that impose a heavy penalty on the party that reneges on its commitment. In the following sections, we first compare the two first strategies, namely the long-term contract and the short-term contracts strategies. Then, in §3.7.1, we show that our findings are robust to the introduction of non-discriminatory reserve prices. Finally, in §3.7.2, we analyze the third strategy (i.e. the hybrid contract). Next, we compare the buyer's expected cost in procuring through two short-term contracts versus a single long-term contract.

Buyer's Expected Cost: Since the suppliers draw their cost afresh in the second period, each supplier's best strategy for the two-auction case without investment would be to bid its realized cost in both the second and the first period. Thus the buyer's total expected cost can be characterized as $\mathbb{E}c^f_{2:n} + \mathbb{E}c^s_{2:n}$, where $c_{m:n}$ denotes the m^{th} lowest cost from a sample size of n. Since cost distribution for the first-period and second-period cost is identical (and independent), the buyer's expected cost can be characterized as $2\mathbb{E}c_{2:n}$, where

$$\mathbb{E}c_{2:n} = \underline{c} + \int_{\underline{c}}^{\bar{c}} \overline{F}^{n-1}(x)\Big\langle nF(x) + \overline{F}(x)\Big\rangle dx. \tag{2}$$

For the single-auction case, the suppliers would have to bid the cost for both the periods at the beginning of the first period. Since suppliers are risk neutral, supplier i's best strategy would be to bid $c^f_i + \mathbb{E}c^s$, where $\mathbb{E}c^s$ represents the mean of the second-period cost distribution. Hence the buyer's expected cost for the single auction would be $\mathbb{E}c_{2:n} + \mathbb{E}c^s$. Thus the difference in the buyer's expected cost between the single-auction setting and two-auction setting can be characterized as

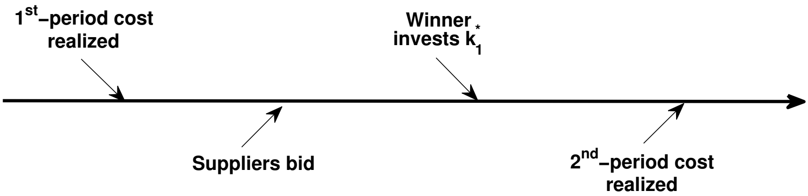
$$\mathbb{E}c^s - \mathbb{E}c_{2:n} = \mathbb{E}c^s - \underline{c} - \int_{\underline{c}}^{\bar{c}} \overline{F}^{n-1}(x)\Big\langle nF(x) + \overline{F}(x)\Big\rangle dx. \tag{3}$$

Lemma 1 *The difference in the buyer's expected cost between the single-auction case and the two-auction case increases in n. Moreover, there exists a threshold supply base size beyond which procuring through two auctions, rather than a single auction, results in a lower expected cost* *for the buyer.*

3.5 Incumbent Supplier's Idiosyncratic Investment

In this section, we investigate the implications of the incumbent supplier making idiosyncratic investments in production process improvement which reduce its per-unit cost for a specific buyer. As mentioned in §3.2, these are for example supplier investments in improving its energy efficiency, in integrating its operations to the buyer's supply chain, or in production learning (e.g. time, effort and resources required) for engineering experiments conducted to optimize production processes specific to buyer's order fulfillment. Production experience is a necessary requirement for these idiosyncratic investments to take place and therefore these investments can only be made by the incumbent supplier (in either the single or the two-auction setting), and not by the entrant suppliers. In addition, costly idiosyncratic investments would intuitively be incurred by the supplier only in counterpart of a supply contract, in order for the supplier to recover the investment (Yu, Liao and Lin, 2006). However, the impact of these idiosyncratic investment on supplier's period-2 cost would be more certain, in contrast to the uncertain impact of plant level investments that we discussed in §3.4.

Specifically, we assume that the incumbent supplier (irrespective of there being one or two auctions) can decide to invest an amount k (which is a decision variable such that $k \geq 0$) to reduce the mean of its second-period cost, by shifting the supplier's second-period cost distribution downwards by an amount $\phi(k)$. Thus a supplier that wins the first-period auction and consequently invests an amount k, draws its second-period cost from the distribution $F(c+\phi(k))$ defined in the limits $[\underline{c}-\phi(k), \bar{c}-\phi(k)]$. We assume that $\phi(k)$ is increasing and concave in k. This assumption captures the decreasing returns of investments, since



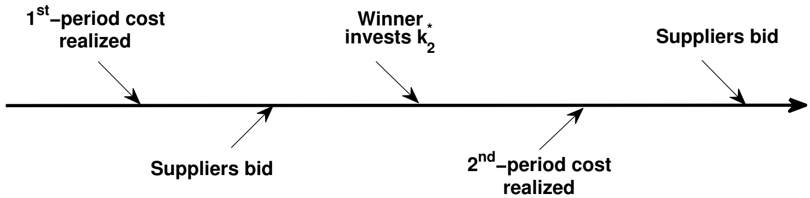


Figure 14: Chronology of events in the single-auction case (above) and the two-auction case (below)

the most interesting investments would be made first. Moreover, we assume that $\phi(k)$ takes value between 0 and $\min(\underline{c}, \bar{c}-\underline{c})$. This assumption implies that idiosyncratic investment never results in the incumbent supplier drawing a second-period cost below 0, and neither in being certain of winning the second auction in the two-auction setting. Also $\phi(0) = 0$. The second-period cost of the non-incumbent suppliers is drawn from the distribution $F(c)$. We denote by c_w^s the second-period cost of the incumbent supplier. In Figure 14 we show the model timeline.

To recap, our main assumptions are as follows:

(1) The buyer procures one unit of homogeneous good in each of the two periods

(2) The buyer uses the second-price auction format to award either two 1-period contracts or a single 2-period contract

(3) The buyer has n qualified suppliers in its supply base in both periods

(4) The suppliers draw a private cost in each period from a symmetric cost distribution (defined in the interval $[\underline{c}, \bar{c}]$), which is common knowledge

(5) The buyer and the selected supplier(s) commit to respect the terms of the contract, regardless of the selected supplier's second-period cost draw.

(6) Suppliers' costs are independent across suppliers and across time

(7) Only the incumbent supplier can invest k to shift down its second-period cost distribution by $\phi(k)$ (i.e. it is not symmetric with the other suppliers in the second period if $\phi(k) > 0$)

(8) The cost improvement $\phi(k)$ is a deterministic function that is increasing and concave in k. It is common knowledge and similar for all the suppliers

(9) An investment cannot result in the incumbent supplier drawing a negative second-period cost, or being assured of winning the second-period auction

We first investigate the optimal investment, k_1^* and k_2^*, that the incumbent supplier would make in the single-auction and two-auction settings respectively.

3.5.1 Supplier Investment in the Single-Auction Setting

In the single-auction setting, the incumbent supplier decides on its optimal investment for the second period. Since in this setting the price offered to the incumbent supplier gets fixed in the first period, the investment should minimize the incumbent supplier's second-period expected cost $\mathbb{E}c_w^s$. Since $\mathbb{E}c_w^s = \mathbb{E}c^s - \phi(k_1)$, we can characterize supplier optimal investment decision k_1^* as the following maximization program

$$k_1^* \equiv \underset{k_1}{\operatorname{argmax}} \Big(\phi(k_1) - k_1 \Big). \tag{4}$$

Since $\phi(k_1)$ is concave in k_1, one can characterize the optimal investment k_1^* through the first order condition. Note that the optimal investment level in the single-auction case is independent of the supply base size n and of the cost distribution since the second-period business is guaranteed in the single-auction setting. Moreover, as suppliers are ex-ante symmetric, each of them would, before the auction, decide to invest the same amount if it wins the auction. Accordingly, they decide their bid in the auction. In §3.6.1 we find suppliers equilibrium bid and then characterize the buyer's expected cost in a single-auction setting.

3.5.2 Supplier Investment in the Two-Auction Setting

In the two-auction setting, the incumbent supplier decides its investment for the second period such that it maximizes its expected second-period surplus. This supplier's expected second-period surplus if it wins the first-period auction and invests k_2 is characterized as

$$U_w^s(k_2, n) = \mathbb{E}_{c_w^s}\mathbb{E}_{c_{1:n-1}^s}[c_{1:n-1}^s - c_w^s | c_{1:n-1}^s \geq c_w^s] \cdot \mathbb{P}(c_{1:n-1}^s \geq c_w^s) - k_2, \quad (5)$$

where $c_{1:n-1}^s$ denotes the lowest second-period cost amongst the $n-1$ non-incumbent suppliers. We can further characterize $U_w^s(k_2, n)$ as (see detailed steps in the Appendix):

$$\begin{aligned} U_w^s(k_2, n) &= \int_{\underline{c}-\phi(k_2)}^{\underline{c}} F(x + \phi(k_2))dx + \int_{\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}^{n-1}(x)F(x + \phi(k_2))dx \\ &+ \int_{\bar{c}-\phi(k_2)}^{\bar{c}} \overline{F}^{n-1}(x)dx - k_2. \end{aligned} \quad (6)$$

The optimal investment, k_2^* can then be characterized as

$$k_2^*(n) \equiv \underset{k_2}{\operatorname{argmax}}\, U_w^s(k_2, n). \quad (7)$$

Typically $U_w^s(k_2, n)$ is not concave in k_2 for any cost distribution and therefore one can not characterize the optimal investment in the two-auction case through first order condition. However, we can determine the effect of supply base size on the optimal investment k_2^*. This is summarized in the next proposition.

Proposition 1 *In the two-auction case, the optimal investment k_2^* of the incumbent supplier is decreasing in the supply base size n.*

Intuitively, a greater supply base size would decrease the likelihood of winning the second-period auction and hence would decrease the expected returns on the investment; therefore reducing the level of investment made by the incumbent supplier.

One might expect k_2^* to always decrease smoothly to 0 as the supply base size n increases. We show in Theorem 1 that this is not always true.

Theorem 1 *For any $m \in \mathbf{R}$; $k_2^*(m)$ is either 0 or not continuously differentiable in $m \geq m^t$ if for an $m^t \geq 2$, the following conditions hold true:*

(1) $\frac{\partial U_w^s(0,m)}{\partial k_2} < 0 \; \forall m \geq m^t$;

(2) $\frac{\partial^2 U_w^s(0,m)}{\partial k_2^2} > 0 \; \forall m \geq m^t$;

(3) $\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2^2} = 0$ *has a unique solution* $\forall m \geq m^t$;

(4) $k_2^*(+\infty) = 0$.

Theorem 1 implies that, in the two-auction case, investment can drop abruptly to 0 after the supply base size crosses a certain threshold. As we will see in Section 3.6.3, this result has important implications on the buyer's expected cost in the two-auction setting for large supply base size. The next proposition characterizes the cost distribution and the functional form of $\phi(k)$ that satisfy the conditions of Theorem 1.

Proposition 2 *For cost distributed uniformly in the interval* $[\underline{c}, \bar{c}]$ *and for* $\phi(k) = \phi_{max}(1 - e^{-\lambda k})$*, conditions (1) to (4) of Theorem 1 are satisfied if* $2 \geq \frac{\bar{c}-\underline{c}}{\phi_{max}} \geq 1$ *and* $\lambda\phi_{max} \leq \frac{\bar{c}-\underline{c}}{\phi_{max}}$.

The right panel of Figure 15 illustrates Theorem 1 and Proposition 2 in showing that the drop to 0 investment could be quite abrupt as supply base size n increases. The intuition behind this result is illustrated in the left panel of Figure 15. Since $U_w^s(k_2, n)$ decreases in n, beyond a certain threshold the maxima of $U_w^s(k_2, n)$ drops below $U_w^s(0, n)$, at which point the supplier stops investing. We also find that this result remains robust for different cost distributions like Uniform and Power distributions. Thus we find that contrary to the single-auction setting, the supply base size can have significant impact on supplier investment in the two-auction setting.

We had also noted that optimal investment in the single-auction setting is independent of the cost distribution. On the contrary, in the two-auction setting one would expect that supplier investment gets more risky as the spread of the cost distribution increases, thus resulting in the incumbent supplier reducing its level of investment k_2^*. The next proposition formalizes this intuition.

Proposition 3 *In the two-auction case the optimal investment* k_2^* *decreases in the spread of the cost distribution for Uniformly distributed cost.*

Figure 16 echoes the findings of Proposition 3 when the underlying costs are distributed according to a power law.

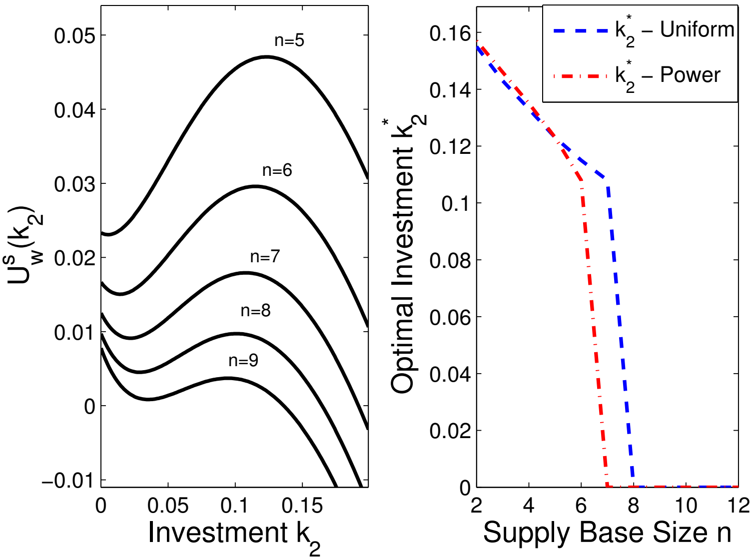


Figure 15: The left panel shows $U_w^s(k_2, n)$ for Uniformly distributed costs. The right panel shows $k_2^*(n)$ when costs are either distributed Uniformly or according to a Power distribution with c.d.f. $F(c) = \frac{c^3 - 0.619^3}{1.319^3 - 0.619^3}$. For both the panels the Uniform distribution of cost is in the interval $[0.7; 1.4]$ and $\phi(k_2) = 0.5(1 - e^{-9k_2})$.

3.5.3 Comparison of the Levels of Investment

Finally, one can compare the investments between the two-auction and single-auction cases. As intuition would suggest, the incumbent supplier is assured of second-period business in a single-auction setting and thus has lower risk on the returns that it can make on its investment. In contrast, in the two-auction setting the incumbent supplier could, even after investing in process improvement, lose the second-period auction. Thus its risk on its investment is higher as compared to the single-auction setting. Therefore, one would expect the investments in the single-auction setting to be higher than the investments in the two-auction setting. The following proposition formalizes this result.

Proposition 4 *Regardless of the supply base size, supplier investment is higher in the single-auction case than in the two-auction case.*

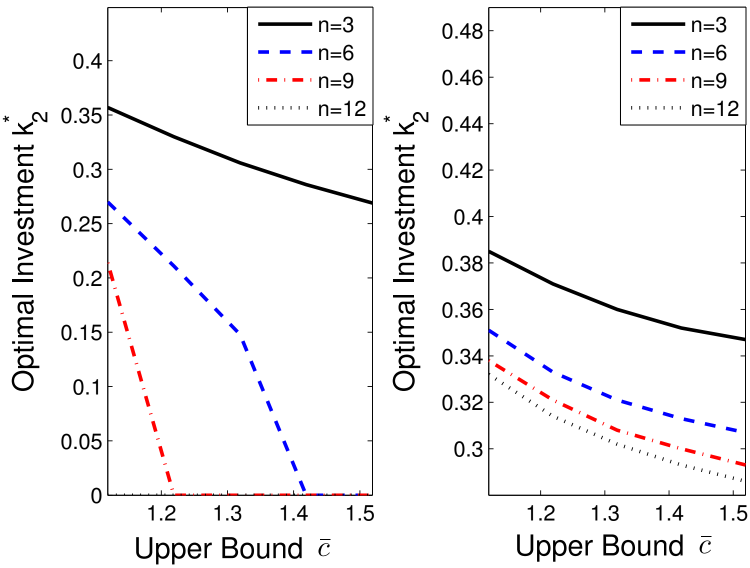


Figure 16: Change in k_2^* as the upper bound of the cost distribution is changed. Cost are distributed according to a Power distribution with c.d.f. $F(c) = \frac{c^3 - 0.619^3}{\bar{c}^3 - 0.619^3}$ in the left panel and with c.d.f $F(c) = \frac{c^{-3} - 0.619^3}{\bar{c}^{-3} - 0.619^3}$ in the right panel. All other parameter values are similar to those in Figure 15.

We had seen earlier that investment in the single-auction setting k_1^* is independent of the supply base size n, whereas in Proposition 1 we saw that the investment in the two-auction setting k_2^* decreases in the supply base size n. This implies that *the difference in the optimal investment between the single-auction setting and the two-auction setting is increasing in the supply base size.*

Similarly, we had also seen that investment in the single-auction setting is independent of the cost distribution, whereas we found that the investment in the two-auction setting typically decreases in the spread of the cost distribution. This implies that *the difference in the optimal investment between the single-auction setting and the two-auction setting typically increases in the spread of the cost distribution*

These results have an interesting implication for the buyer selecting between organizing a single auction or two auctions. We saw in Lemma 1 that, without supplier investment, buyer's relative savings from the two-auction case (as compared to the single-auction case) are increasing in the supply base size. However, now we see that supplier investment in cost reduction efforts is increasing in a single-auction setting relative to a two-auction setting as the supply base size increases. Thus, upfront it is not clear whether a buyer would prefer a single auction or two auctions as its supply base size increases. More generally, for a given supply base size, what would be better (less costly) for the buyer: a long-term contract or short-term contracts? To answer this question, we first need to characterize the buyer's expected cost in both the settings, and then compare those costs. We perform this task in the next section.

3.6 Buyer's Expected Cost and Suppliers' Surplus

In this section, we characterize the buyer's expected cost in both the single and the two-auction settings. For this, we first characterize the equilibrium bidding strategies of the suppliers in both the auction formats and then characterize the difference in the buyer's expected cost between the single and the two-auction settings. We also compare the single-auction and two-auction setting for differences in supplier's surplus and system cost.

3.6.1 Buyer's Expected Cost in the Single-Auction Setting

Since it is a one-shot second-price auction event, each supplier would bid its expected cost for both the periods. The first-period cost is known to the supplier. The expectation for the second-period cost would involve the optimal investment that the supplier would make if it wins the auction. Since suppliers are ex-ante (before the auction) symmetric, each supplier's expected second-period cost would be the same, i.e., $\mathbb{E}c_w^s + k_1^*$, where $\mathbb{E}c_w^s$ and k_1^* have been characterized in §3.5.1. Thus the equilibrium bid of supplier i in the single second-price auction would be

$$c_i^f + \mathbb{E}c_w^s + k_1^*, \tag{8}$$

such that the buyer's expected cost in a single second-price auction can be characterized as

$$\mathbb{E}B_1 = \mathbb{E}c_{2:n}^f + \mathbb{E}c_w^s + k_1^*. \tag{9}$$

From Lemma 1 we know that $\mathbb{E}c_{2:n}^f$ is decreasing in n and therefore the buyer's expected cost in the single-auction setting is decreasing in the supply base size n.

3.6.2 Buyer's Expected Cost in the Two-Auction Setting

In the two-auction setting, winning the first-period auction does not ensure second-period business (for which the incumbent supplier would have to compete again in the second-period auction). However, winning the first-period auction enables the supplier **to invest in process improvement** (and consequent cost reduction) thus increasing its chances of winning the second-period auction. Each supplier bidding for the first-period auction would thus strategically take into account the impact that its first-period bid would have on its second-period expected surplus.

The second-period second-price auction is similar to single-shot second-price auction, therefore each supplier would bid its realized cost of the second-period in the second-period auction. Denote by U_l^s the second-period expected surplus of a non-incumbent supplier (see detailed expression for U_l^s in appendix):

$$U_l^s = \mathbb{E}_{c_i^s}\mathbb{E}_{\zeta^s}[\zeta^s - c_i^s|\zeta^s \geq c_i^s] \cdot \mathbb{P}(\zeta^s \geq c_i^s), \tag{10}$$

where ζ^s represents the lowest cost amongst the $n-2$ other non-incumbent suppliers and the incumbent supplier. Moreover, denote by δ the additional second-period expected surplus that a supplier would make by winning the first-period auction as compared to losing the first-period auction, i.e.,

$$\delta = U_w^s(k_2, n) - U_l^s. \tag{11}$$

Then the equilibrium bidding strategy of the supplier in the first-period auction can be characterized by the following lemma.

Lemma 2 *In the two-auction setting, the equilibrium bidding strategy of the suppliers in the first auction can be characterized as*

$$\beta^*_{double}(c_i^f) = c_i^f - \delta. \tag{12}$$

Intuitively, δ is the additional surplus that a supplier expects to gain in the second period by winning the first-period auction and therefore it bids away these gains in its first-period auction bid. This result is consistent with Klotz and Chatterjee (1995) and Elmaghrabhy and Oh (2004) who find that in a two-auction setting suppliers bid away their second-period gains in the first period. The buyer's expected cost in two second-price auctions can then be characterized as

$$\mathbb{E}B_2 = \mathbb{E}c_{2:n}^f + \mathbb{E}c_{2:n}^s - \delta, \tag{13}$$

where $\mathbb{E}c_{2:n}^s$ is the second-period expected second-lowest cost amongst the incumbent supplier and the remaining $n-1$ non-incumbent suppliers. One can characterize $\mathbb{E}c_{2:n}^s$ as

$$\mathbb{E}c_{2:n}^s = \underline{c} + \int_{\underline{c}}^{\bar{c}} \overline{F}^{n-2}(x)\Big\langle \overline{F}(x)\overline{F}(x+\phi(k_2)) + (n-1)\overline{F}(x+\phi(k_2))F(x) + \overline{F}(x)F(x+\phi(k_2))\Big\rangle dx. \tag{14}$$

Next we compare the buyer's expected cost between the single and the two-auction case.

3.6.3 Comparison of the Buyer's Expected Cost

When deciding between long-term and short-term contracts, the buyer weighs two major factors: (1) through short-term contracts the buyer discovers the lowest-cost supplier in each period, whereas it only discovers the lowest-cost supplier in the first period with a long-term contract. Thus a long-term contract results in an opportunity cost for the buyer of not discovering the lowest-cost supplier in period 2. (2) However, Proposition 4 states that the buyer can incentivize a greater investment (and therefore cost reduction) from the incumbent supplier through a long-term rather than short-term contract. Figure 17 shows that for smaller supply base sizes, the difference in savings from incumbent supplier's cost reduction effort between long-term versus short-term contracts is higher than the opportunity cost of not discovering the lowest-cost supplier in the second-period. Hence the buyer prefers longer-term contracts when supply base size is small. As supply base size gets bigger, the buyer's opportunity cost of not discovering the lowest-cost supplier in the second period increases and eventually surpasses the difference in savings from incumbent supplier's cost reduction effort between the long-term contract and the short-term contract. Thus the buyer starts preferring shorter-term contracts. However, beyond a certain supply base size, the incumbent supplier, in the short-term contract case, stops investing as a result of which the difference in buyer's savings from suppliers' cost improvement between long versus short-term contracts suddenly increases and buyer again starts to prefer long-term

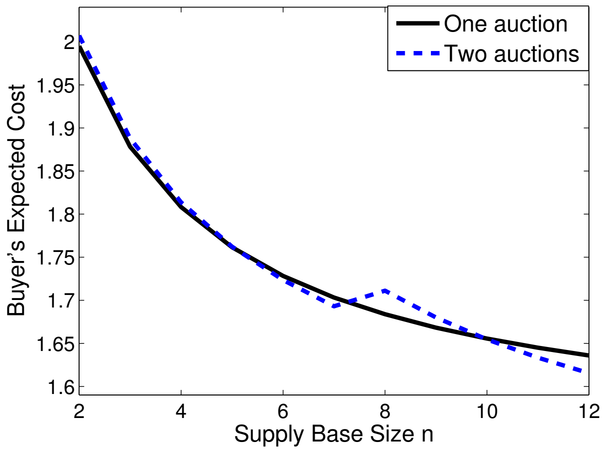


Figure 17: Buyer's expected costs as n changes. Costs are uniformly distributed in the interval $[0.7; 1.4]$. All other parameter values are similar to those in Figure 15.

contract.[8] But then gradually with further increase in supply base size the opportunity cost of not organizing a second-period auction creeps up and thus the buyer again tilts towards giving short-term contracts. Overall, we find that the complex interaction of the supply base size on the buyer's expected cost in the two-auction setting implies that the buyer might prefer a single auction (i.e. a long-term contract) or two auctions (i.e. short term contracts) depending on the size of its supply base.

In Figure 18 we investigate the difference in the buyer's expected cost in both the auction settings as parameters of $\phi(k)$ and the cost distribution are changed. In the top two plots of Figure 18, we see that, regardless of the supply base size, the difference in the buyer's expected cost between the auction settings ($\mathbb{E}B_1 - \mathbb{E}B_2$) tends to diminish as the efficiency of supplier investment (measured by λ or ϕ_{max}) increases. However, this does not always remain true as supplier investment can drop

[8]Unlike in the single-auction case, the buyer's expected cost in the two-auction case is not necessarily monotonic in the supply base size.

abruptly when supply base size goes beyond a certain threshold, which is different for different efficiency of supplier investment. We define an investment being more efficient when the same amount of investment k in process improvement results in greater reduction of production cost. The intuition behind this finding is that higher efficiency of investment enables, in the two-auction case, the incumbent supplier to invest higher amounts, which increases its chances of winning the second auction as well. Thus the investment of the incumbent supplier in the two-auction case approaches the investment level of the incumbent supplier in the single-auction case (who is sure of getting the second-period business). Thus, the buyer's expected cost in both the auction settings converges as the efficiency of the supplier's investment increases. Similarly, we see in the bottom plot of Figure 18 that the difference in the buyer's expected cost between the auction settings diminishes as the range of the cost distribution decreases. The reason for this finding is similar to the one above, i.e., with decreasing range of suppliers' cost distribution it becomes more likely for the incumbent supplier, in the two-auction case, to win the second auction also. Thus its investment in the two-auction case converges towards the level of investment of the incumbent supplier in the single-auction case and therefore buyer's expected costs in both the auction settings also converge.

The three subplots of Figure 18 indicate that in industries where the benefits derived from suppliers making idiosyncratic investments are more important relatively to suppliers' cost variability, the difference between organizing two short-term auctions and a single auction is smaller. Namely, selecting the right contract length is especially important when idiosyncratic investments result in moderate cost improvements.

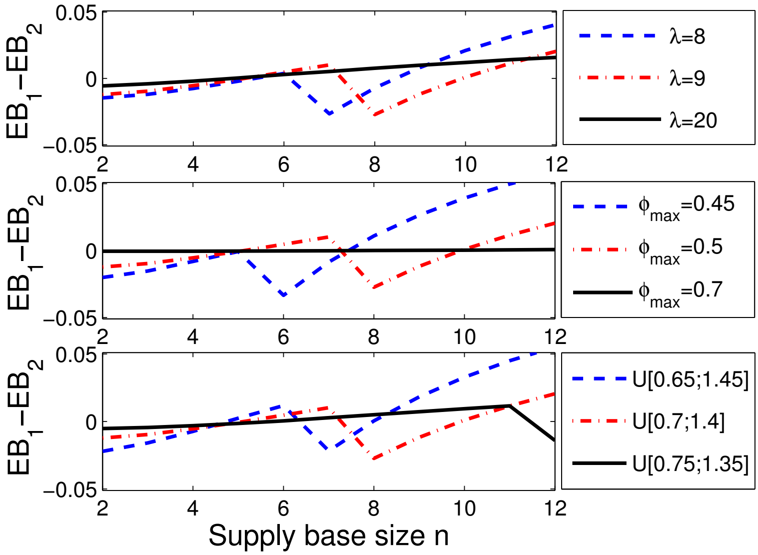


Figure 18: Difference in buyer's expected cost between the two auction settings. Costs are uniformly distributed in the interval $[0.7; 1.4]$ (top two plots) and in the interval $[0.7 + a; 1.4 - a]$ (bottom plot). All other parameter values are similar to those in Figure 15.

3.6.4 Minimum Return on Investment Constraint

A supplier that needs to raise capital for investing in production cost improvement might do so only if it expects a certain minimum amount of return from its investment. A low expectation of return from such an investment would deter the supplier from investing in production process improvement. In this subsection, we introduce a return on investment constraint in our model. Since any investment made by the winning supplier only affects its second-period surplus, we calculate return on investment as the difference of the supplier's expected second-period surplus if it invests and its expected second-period surplus if it does not, divided by the investment. We denote by $\alpha > 0$ the minimum return on investment desired by the supplier. Thus the model analysis can be modified by adding the constraint $(\phi(k_1) - k_1)/k_1 \geq \alpha$ to program (4) and by adding the constraint $(U_w^s(k_2, n) - U_w^s(0, n))/k_2 \geq \alpha$ to program

(7).

In Figure 19 we present the numerical analysis on buyer's expected cost after the minimum return on investment constraint is added to the model. Comparing the left hand side of Figure 19 with Figure 17 we find that in the two-auction case the constraint on return on investment results in the incumbent supplier reducing its investment to 0 at a much lower supply base size as compared to no constraint on return on investment[9]. Moreover, the jump in the buyer's expected cost (at the supply base size at which supplier stops investing) is much greater with the constraint on return on investment than without it. This is because the drop in investment (to the 0 level) as the supply base size increases is much greater with the constraint on level of investment than without it. We see this more clearly in the right hand side of Figure 19 where the jump in $\mathbb{E}B_2$ is higher and occurs at a lower supply base size for higher value of α.

3.6.5 Comparison of the Expected Suppliers' Surplus

We now compare the suppliers' expected surplus in both the single-auction and the two-auction settings when they can invest in cost improvement.

Proposition 5 *For a given supply base size, the suppliers' expected surplus (before the first-period auction) is higher in the two-auction case as compared to the single-auction case.*

We saw in Equation (8) and Equation (12) that, in both the auction settings, the suppliers are willing to bid away (in the first-period

[9]Buyer's expected cost remains unchanged in the single-auction case because the return on investment for the winning supplier in the single auction case is more than 30%.

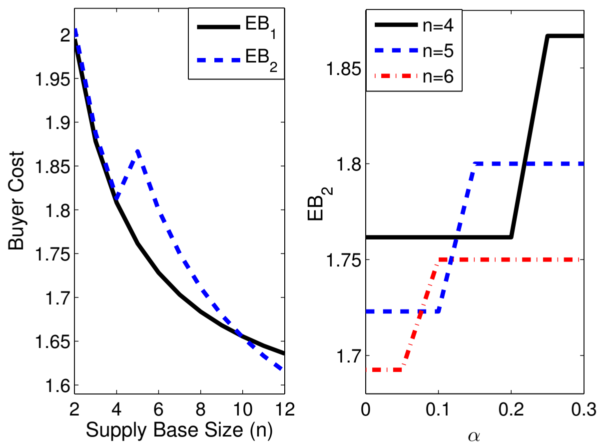


Figure 19: Buyer's expected cost with return on investment. $\alpha = 0.3$ (left plot). Costs are uniformly distributed in the interval $[0.7; 1.4]$. All other parameter values are similar to those in Figure 15.

auction) the second-period surplus that they expect to make by winning the first-period auction. But, in the two-auction setting, the suppliers that do not win in the first auction can still win the second auction and thus make a positive gain. However, in the single-auction case, the non-incumbent suppliers do not get a second chance, and therefore their second-period gains are zero. Thus suppliers are better-off, in expectation, in participating in two auctions rather than a single auction.

3.6.6 Comparison of the Expected System Cost

Finally, we compare the expected system cost (i.e., the expected production cost plus the investment in process improvement) in both the auction settings. For that, we denote the expected system cost, in the single and the two-auction cases, as $\mathbb{E}PC_1 = \mathbb{E}c^f_{1:n} + \mathbb{E}c^s_w + k^*_1$ and $\mathbb{E}PC_2 = \mathbb{E}c^f_{1:n} + \mathbb{E}c^s_{1:n} + k^*_2$, respectively. We characterize the difference of the expected system cost between the single and the two-auction settings as $\Delta\mathbb{E}PC$:

$$\Delta\mathbb{E}PC = \mathbb{E}PC_1 - \mathbb{E}PC_2 = \mathbb{E}c^s_w + k^*_1 - \mathbb{E}c^s_{1:n} - k^*_2. \tag{15}$$

In Figure 20 we present numerical results on system cost. The top plot of Figure 20 shows that, unlike the buyer's expected cost, the expected system cost is monotonically decreasing in the supply base size for both the single and the two-auction setting. This is because the system cost does not include the supplier's surplus whereas the buyer's expected cost does. Thus the system cost does not change abruptly (unlike the buyer's cost) when the supplier stops investing beyond the threshold supply base size. Also, typically the single-auction system cost is higher than the two-auction system cost. This is because the investment in the single-auction setting is higher and moreover the expected second-period cost in the single-auction setting is also higher since it is the mean of the winning supplier's cost whereas in the two-auction setting it is the lowest cost amongst the n suppliers.

In the other plots of Figure 20 we find that the difference in system cost converges to 0 as investments are more efficient or as the range of cost distribution reduces. These findings echo the results from Figure 18; because with higher investment efficiency or lower cost range the supplier who won the first auction, in the two-auction setting, is more likely to win the second auction also and therefore the expected second-period cost is similar in both the single-auction and the two-auction setting. Finally, we find that the difference in system cost is increasing in the supply base size. This is because the investment in the two-auction setting is decreasing relative to the investment in the single-auction setting as n increases and moreover the gap between the lowest draw in the second period and the mean of the second-period cost increases as n increases.

Therefore, Figure 20 confirms the managerial insights derived from

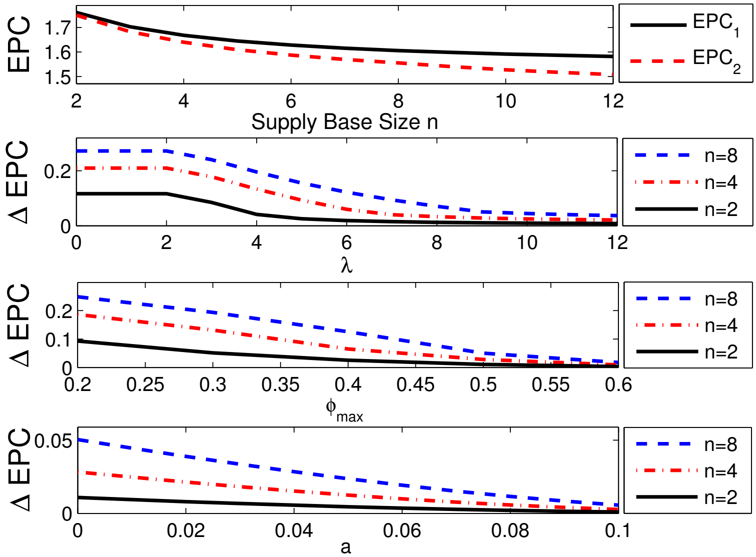


Figure 20: Difference in expected system cost. Costs are uniformly distributed in the interval $[0.7; 1.4]$ (top three plots) and in the interval $[0.7 + a; 1.4 - a]$ (bottom plot). All other parameter values are similar to those in Figure 15.

Figure 18, namely that selecting the adequate contract length is less critical when the idiosyncratic investments are result in more consequent supplier's cost improvements relatively to the supplier's cost variability.

3.7 Reserve Prices

This section investigates how the results would change if the buyer uses optimally set reserve prices in both auction settings. In a classical single shot second-price auction, reserve prices are used to better manage buyer's procurement cost when the buyer has access to a viable outside option (which could be a non-participating supplier or buyer's in-house production). In our single-auction setting, the buyer's rationale for setting optimal reserve price remains similar to the classical single shot second-price auction. Also, in the two-auction setting too the rationale for using reserve price remains same as above as long as there is a single reserve price set in both the first and the second-period auction (although the reserve prices could be different in the first and second auction). However, the rationale for using reserve prices changes in the two-auction setting if the buyer can discriminate between the supplier who won the first period and those who did not win the first period auction. In this case, discriminatory reserve prices allow the buyer to better balance the trade-off between incentivizing the incumbent supplier to invest in process improvement (by setting a very high second-period reserve price for the incumbent supplier and very low second-period reserve price for the non-incumbent suppliers) versus leveraging supplier competition in the second-period (by setting a single second period reserve price for both the incumbent and non-incumbent suppliers).

In this section, we therefore analyze two different models with reserve prices, depending upon whether the buyer can discriminate between suppliers (note that supplier discrimination can only occur in the second-period auction of the two-auction setting, since suppliers would be ex-ante symmetric in the first-period auction of either the single or two-auction setting). First, we consider in §3.7.1 that, the buyer does not discriminate between the suppliers in the second-period of the two-auction setting. Then, we allow, in §3.7.2, the buyer to offer a different reserve price, in the second auction, to the incumbent supplier and to the non-incumbent supplier.

3.7.1 Non-Discriminatory Reserve Prices

With non-discriminatory reserve prices, the buyer offers the same reserve price to every supplier in each auction. In the single-auction setting, the (unique) reserve price is denoted r_1. If no supplier bids below r_1, the buyer pays c_{out} (i.e. the per-unit cost of the outside option) for the first auction, and re-organizes an auction in the second period, for which it sets a reserve price r_{nw}. This new auction thus gathers n suppliers that could not invest. If no supplier bids below r_{nw} in the re-organized auction, then the buyer again pays c_{out} for the second period. In the two-auction setting, the suppliers face one reserve price in the first auction, r_2^f, and another in the second auction, r_2^s. If no supplier bids below r_2^f (r_2^s) in the first (second) auction, the buyer pays c_{out} for this period. When no supplier bids below r_2^f in the first auction, the second auction is similar to the re-organized auction of the single-auction setting (when no supplier meets r_1). Therefore, we consider the same r_{nw} for both settings. Note that the buyer commits to the reserve prices before the first-period auction. Also the subscript rp denotes a value specific to the case with reserve prices.

We first characterize the buyer's problem of selecting the optimal reserve prices in both the single and the two-auction settings. Finding closed form solutions to optimal reserve price is very hard in dynamic settings, especially when there are cost asymmetries (as in the second auction of the two-auction case). Therefore we find the optimal reserve prices numerically. In the single-auction setting, we can characterize the buyer's expected cost as

$$\begin{aligned}
\mathbb{E}B_{1,rp}(n, r_1) &= \Pr\Big(b_{1:n} > r_1(n)\Big) * \Big(c_{out} + \mathbb{E}B_{nw}(n)\Big) \\
&+ \Pr\Big(b_{2:n} \leq r_1(n)\Big) * \mathbb{E}\Big[b_{2:n} | b_{2:n} \leq r_1(n)\Big] \\
&+ \Pr\Big(b_{1:n} \leq r_1(n) \leq b_{2:n}\Big) * r_1(n), \qquad (16)
\end{aligned}$$

where suppliers bid $b_i = c_i^f + \mathbb{E}c_w^s + k_{1,rp}^*$, as in Equation (8) and where $\mathbb{E}B_{nw}(n)$ represents the buyer' expected second-period cost if no supplier accepts its first-period reserve price r_1, and is characterized as:

$$\begin{aligned}\mathbb{E}B_{nw}(n) &= \Pr\left(c^s_{1:n} > r_{nw}\right) * c_{out} + \Pr\left(c^s_{2:n} \leq r_{nw}\right) * \mathbb{E}\left[c^s_{2:n} | c^s_{2:n} \leq r_{nw}\right] \\ &+ \Pr\left(c^s_{1:n} \leq r_{nw} \leq c^s_{2:n}\right) * r_{nw}. \end{aligned} \tag{17}$$

From Equation (17) we find the optimal r_{nw}. Then, from Equation (16), we obtain the optimal r_1 and $\mathbb{E}B_{1,rp}$.

We then characterize the buyer's problem for the two-auction setting by working backward, i.e., we first calculate $k^*_{2,rp}$ (the optimal investment made by the incumbent supplier) and δ_{rp} (the additional second-period expected surplus that a supplier would make by winning the first-period auction as compared to losing the first-period auction, defined in Equation (11)) for any n and r^s_2.[10] We then find the buyer's expected cost in the second auction if there is a winner in the first period, and denote it by $\mathbb{E}B^s_{2,w}$, for any n and r^s_2. The buyer's expected cost in the second auction if no supplier meets the first-auction reserve price, $\mathbb{E}B_{nw}$, and the related optimal r_{nw} remains similar to one characterized by Equation (17). Knowing δ_{rp} (and thus the first-auction bids $b^f_i = c^f_i - \delta_{rp}(n, r^s_2)$, see Equation (12)), we obtain the buyer's first-period expected cost. We then find the reserve prices that minimize the

[10]As reserve prices are announced upfront, when the suppliers bid their cost less δ in the first auction, they are aware of whether they meet r^f_2 or not. Unlike a supplier that meets r^f_2, a supplier who does not meet r^f_2 (and therefore does not bid in the first auction) would not be certain that at least one supplier will meet r^f_2 and invest. Thus, there would be a difference in U^s_l, and thus in δ_{rp}, between these two suppliers. However, without any loss of generality, the buyer can assume that all the suppliers bid as if they meet the reserve price, as only those bids are considered to determine the winner. This eases the calculations by making δ_{rp} independent of r^f_2.

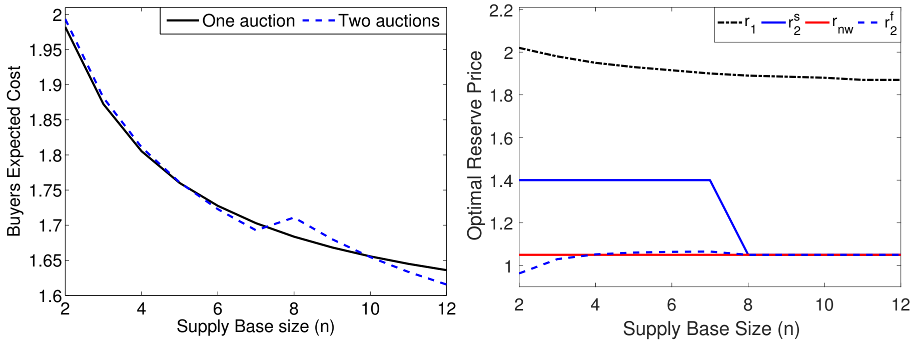


Figure 21: Optimal reserve prices (right plot) and buyer's expected cost (left plot) in n with non-discriminatory reserve prices. $c_{out} = \bar{c}$. All other parameters are similar to those in Figure 15.

overall buyer's cost, which we characterize as:

$$\begin{aligned}
&\mathbb{E}B_{2,rp}(n, r_2^f, r_2^s) \\
&\quad = \Pr\left(b_{1:n}^f > r_2^f(n)\right) * \left(c_{out} + \mathbb{E}B_{nw}(n)\right) \\
&\quad + \Pr\left(b_{1:n}^f \leq r_2^f(n)\right) * \mathbb{E}\Big[B_{2,w}^s(n, r_2^s) | b_{1:n}^f \leq r_2^f(n)\Big] \\
&\quad + \Pr\left(b_{1:n}^f \leq r_2^f(n) \leq b_{2:n}^f\right) * r_2^f(n) \\
&\quad + \Pr\left(b_{2:n}^f \leq r_2^f(n)\right) * \mathbb{E}\Big[b_{2:n}^f | b_{2:n}^f \leq r_2^f(n)\Big]. \qquad (18)
\end{aligned}$$

Our numerical findings are illustrated in Figure 21. From Equation (4), we deduce that $k_{1,rp}^*$ is independent of r_1 in the single-auction setting. In the two-auction setting, the right plot shows that, as long as the incumbent supplier invests a positive amount, the buyer sets $r_2^s = \bar{c}$ such that it does not put any additional pressure on the suppliers' second-period expected profit, as compared to the original model without reserve prices, and hence does not deter investment from the incumbent supplier. Consequently, optimal investments are as in Figure 15 (right). However, when the supply base size is such that the incumbent supplier does not invest, the suppliers are symmetric and the second-period reserve price r_2^s drops to r_{nw}. Then, to understand how r_2^f changes in the supply base size n, one must first notice that investment, in the two-auction setting, benefits the buyer in two ways. On the one hand, the buyer makes savings in the first auction as the suppliers bid away δ_{rp} in that auction to optimize their chance to win it. On the other hand, the buyer makes savings in the second auction since one of the suppliers has shifted down its cost distribution through its investment. When the incumbent supplier does not invest, the buyer puts a reserve price r_2^f that is equal to r_{nw}, as the first and the second auctions are similar, and do not affect each other. However, the buyer sets $r_2^f < r_{nw}$, to put pressure on the suppliers in the first period, if it can make greater savings from the investment in the first auction, rather than in the second auction. In contrast, it sets $r_2^f > r_{nw}$ to ensure that there will be a winner in the first auction, if it can make greater savings from the investment in the second auction. Also note that the optimal reserve price in the single-auction setting, r_1, decreases in n. Indeed, if no supplier bids below r_1, the buyer pays c_{out} for the first auction, plus $\mathbb{E}B_{nw}(n)$ for the re-organized auction. As $c_{out} + \mathbb{E}B_{nw}(n)$ decreases in n, the buyer is willing to take more risk in setting an aggressive reserve price r_1.

We show in Figure 21 (left) that introducing non-discriminatory reserve prices into our original model does not impact our results. Although it improves the buyer's cost in both settings (compare Figure 21 (left) and Figure 17), as it offers an extra option to the buyer, it does not change the optimal investments and preserve the trade-off between a long-term contract, that incentivizes investment, and short-term contracts, that foster competition. Importantly, Theorem 1 remains valid with non-discriminatory reserve prices.

3.7.2 Discriminatory Reserve Prices

With discriminatory reserve prices the buyer can offer, in the second auction, a different reserve price to the incumbent supplier and to the non-incumbent suppliers.[11] As a result it is not necessary that the second-period lowest bidder always wins the auction. Indeed, the lowest bidder's bid might be above its reserve price while a higher bidder's bid might be below its reserve price.

By discriminating in favor of the incumbent, i.e., by setting a high reserve price for the incumbent supplier relative to the reserve price of the non-incumbent suppliers, the buyer can offer a partial protection to the incumbent supplier in the second-period auction and thus incentivize the incumbent supplier to invest in process improvement. This is similar to offering a long-term contract in which the buyer gave full protection to the incumbent supplier for the second-period business, which motivated a higher investment from the incumbent supplier. On the other hand, by setting similar reserve prices for both the incumbent and non-incumbent suppliers, the buyer reduces business assurance to the incumbent supplier but increases second-period price competition between the incumbent and non-incumbent suppliers by offering a greater chance to the non-incumbent suppliers to win buyer's business in the second period. This is similar to two short-term contracts in which the buyer gives no protection to the incumbent supplier for the second auction, thus reducing the level of investment from the incumbent, but resulting in a higher level of competition between the incumbent and the non-incumbent suppliers.

[11]Note that discrimination can only occur in the second-period of the two-auction setting since in the first-period auction all the suppliers are symmetric.

Intuitively, by appropriately selecting the level of the incumbent supplier's reserve price and the non-incumbent suppliers' reserve price, the buyer can better balance the trade-off between benefits from the incumbent supplier's process improvement investments and benefits from second-period supplier price competition. Hence we think of a contract with discriminatory reserve prices as a hybrid contract that best balances the trade-off in buyer's sourcing strategy.

We use subscript h to denote a value specific to such a hybrid contract and use $(r^s_{h,w})$ to denote second-period reserve price of the incumbent supplier and use $(r^s_{h,l})$ to denote the second-period reserve price of the non-incumbent suppliers. By setting $r^s_{h,l} \leq \underline{c}$, the buyer ensures the second-period business to the incumbent supplier and therefore mimics the single-auction setting as in §3.7.1. Similarly, by setting $r^s_{h,l} = r^s_{h,w} = \bar{c}$, the buyer offers the same reserve price to every supplier and therefore mimics the two-auction setting as in §3.7.1. As the buyer can replicate both the single-auction and the two-auction settings with a hybrid contract, it always prefers to use a hybrid contract with optimally set reserve prices than to use either a long-term contract or short-term contracts. We state this formally in the next corollary.

Corollary 1 *The buyer's expected cost is always lower with a hybrid contract than with either a long-term contract or short-term contracts.*

To determine the reserve prices that would result in the optimal hybrid contract, we characterize the buyer's expected cost as

$$
\begin{aligned}
&\mathbb{E}B_h(n, r^s_{h,w}, r^s_{h,l}, r^f_h) \\
&\quad = \Pr\left(b^f_{1:n} > r^f_h(n)\right) * \left(c_{out} + \mathbb{E}B_{nw}(n)\right) \\
&\quad + \Pr\left(b^f_{1:n} \leq r^f_h(n)\right) * \mathbb{E}\left[B^s_{h,w}(n, r^s_{h,w}, r^s_{h,l}) | b^f_{1:n} \leq r^f_h(n)\right] \\
&\quad + \Pr\left(b^f_{1:n} \leq r^f_h(n) \leq b^f_{2:n}\right) * r^f_h(n) \\
&\quad + \Pr\left(b^f_{2:n} \leq r^f_h(n)\right) * \mathbb{E}\left[b^f_{2:n} | b^f_{2:n} \leq r^f_h(n)\right],
\end{aligned} \tag{19}
$$

with the expected buyer's cost in the second period if one of the supplier wins the first-period auction being defined as

$$
\begin{aligned}
&\mathbb{E}B^s_{h,w}(n, r^s_{h,w}, r^s_{h,l}) \\
&\quad = \Pr(c_w > r^s_{h,w}, c_{1:n-1} > r^s_{h,l}) \cdot c_{out} \\
&\quad + \Pr(c_w \leq r^s_{h,w}, c_{1:n-1} > r^s_{h,l}) \cdot r^s_{h,w} \\
&\quad + \Pr(c_w > r^s_{h,w}, c_{1:n-1} \leq r^s_{h,l}) \cdot \mathbb{E}_{c_{n-1}}(\min(r^s_{l,w}, c_{2:n-1}) | c_{1:n-1} \leq r^s_{h,l}) \\
&\quad + \Pr(c_w \leq r^s_{h,w}, c_{1:n-1} \leq r^s_{h,l}, c_w \leq c_{1:n-1}) \\
&\qquad \cdot \mathbb{E}_{c_w, c_{1:n-1}}(\min(r^s_{h,w}, c_{1:n-1}) | c_w \leq r^s_{h,w}, c_{1:n-1} \leq r^s_{h,l}, c_w \leq c_{1:n-1}) \\
&\quad + \Pr(c_w \leq r^s_{h,w}, c_{1:n-1} \leq r^s_{h,l}, c_w > c_{1:n-1}) \\
&\qquad \cdot \mathbb{E}_{c_w, c_{n-1}}(\min(r^s_{l,w}, c_w, c_{2:n-1}) | c_w \leq r^s_{h,w}, c_{1:n-1} \leq r^s_{h,l}, c_w > c_{1:n-1}).
\end{aligned} \tag{20}
$$

We depict our numerical results in Figure 22. This shows that the optimal hybrid contract enables the buyer to achieve the benefits of both competition and supplier investment. Indeed, the buyer benefits from competition by two means. First, it sets $r^s_{h,l} > \underline{c}$, such that the incumbent supplier is not guaranteed to win the second auction, which implies

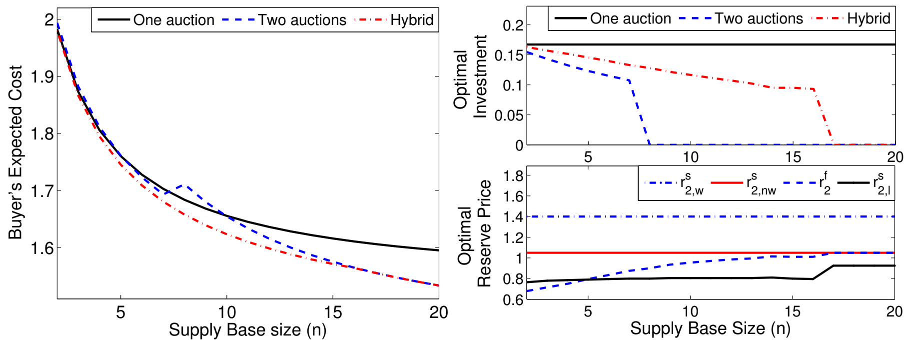


Figure 22: Optimal investment (top right plot), reserve price (bottom right plot), and buyer's expected cost (left plot) in n with discriminatory reserve prices. All parameters are similar to those in Figure 21.

a competitive auction in both periods. Second, it sets $r^s_{h,l}$ low enough to take a chance that at least one non-incumbent supplier draws a low cost, such that the buyer would pay at most $r^s_{h,l}$ for the second auction. In addition to taking advantage of the competition, the buyer ensures a high investment by providing sufficient protection to the incumbent supplier in the second auction, by setting $r^s_{h,w} > r^s_{h,l}$. This reduces the likelihood that the incumbent loses the second auction (and its investment), hence resulting in a higher investment (than in the classical two-auction setting) and therefore a lower expected cost for the buyer. Note that a high $r^s_{h,w}$ not only induces higher investment, but also increases the expected payment to the incumbent supplier if it wins the second auction. However, the incumbent supplier bids away this expected extra profit in the first auction to increase its chance of winning this auction, and a high $r^s_{h,w}$ therefore does not increase the buyer's expected cost. These observations are in line with Cisternas and Figueroa (2015). In a similar setting, they show that giving an advantage in the second auction to the incumbent supplier results in an optimal mechanism. However, they discriminate in favor of the incumbent supplier through artificially inflating the non-incumbent suppliers' second-period bid, rather than through reserve prices.

Figure 22 (bottom-right) summarizes the dynamics of the reserve prices, in the optimal hybrid contract, in n. As in §3.7.1, the buyer does not put pressure on the second-period expected profit of the incumbent supplier, by setting $r^s_{h,w} = \bar{c}$. This motivates investment, and consequently a high δ_h. The benefits from winning the first auction, δ_h, is even greater since $r^s_{h,l} < r^s_{h,w}$. As a greater δ_h increases the buyer's benefits in the first auction, due to the investment, the buyer sets r^f_h lower than in the non-discriminatory reserve prices case. Moreover, as δ_h decreases in n, r^f_h increases gradually in n, as long as the incumbent supplier invests.

In the models discussed before §3.7.2, the buyer either fully protected the incumbent supplier in the second period (through a long-term contract), or it did not protect it at all (through short-term contracts). In this subsection, by deciding $r^s_{h,l}$, the buyer can select the accurate level of protection that it wants to offer to the incumbent supplier in the second auction. Although we see that $r^s_{h,l}$ is relatively constant as long as the supply base size is such that the incumbent supplier invests, one can deduce that the level of protection offered to the incumbent supplier actually decreases in n. Indeed, as n increases, the risk for the incumbent supplier that at least one non-incumbent supplier bids below $r^s_{h,l}$ increases. As $r^s_{h,l}$ remains constant, the actual level of protection awarded is decreasing in n. Thus the buyer offers more protection (to motivate investment) to the incumbent supplier in the second auction when supply base size is smaller, which is consistent with our findings from §3.6.3, stating that a buyer prefers a longer-term contract for smaller supply base sizes.

Moreover, in contrast with Theorem 1, we find that $\mathbb{E}B_h$ decreases monotonically in the supply base size, despite that k_h^* still drops suddenly to 0 as supply base size increases. As the optimal hybrid contract gathers the instruments from both the long-term (higher investment) and short-term contracts (fiercer competition), the buyer can prevent any jump in $\mathbb{E}B_h$ by subtly coordinating its reserve prices.

In conclusion, one can better balance the fundamental trade-offs between benefits of supplier investment and supplier competition with discriminatory reserve prices. We find that such a hybrid contract is closer to a long-term contract when benefits from investment are higher relative to supplier price competition, i.e., when supply base size is smaller. Whereas a hybrid contract is closer to short-term contracts when benefits from supplier price competition are higher relative to benefits from supplier investment, i.e., when supply base size is larger. Thus our results with discriminatory reserve prices are consistent with our previous results without reserve prices. From a managerial perspective, hybrid contracts would change the critical decision from jointly deciding contract length and supply base size to selecting the optimal set of reserve prices, in order to determine whether the hybrid contract would be closer to a long-term contract or to two short-term contracts. This is because hybrid contracts always dominate the long-term contract case as well as the repeated short-term contracts case, such that the contract length would not remain a decision variable. Moreover, the supply base size decision with the hybrid contract would also be straightforward as more suppliers would always be preferable.

3.8 Conclusion

In dynamic markets where supplier technology evolves fast, a buyer regularly auctions off new contracts to stay abreast of the best price that it can receive from its supply base. However, short-term contracts might not incentivize the supplier to invest in process improvement efforts that can reduce its production cost; because such an investment would be risky for the supplier since it is not sure of winning consequent auctions. On the contrary a longer-term contract can better incentivize the supplier to invest in production cost reduction since it is assured of future business. Thus, a short-term contract allows the buyer to stay abreast of the current best market price but the long-term contract allows the buyer to gain from supplier's production process improvement efforts. In this paper we use a second-price auction setting to compare a buyer organizing two auctions (corresponding to short-term contracts) to a buyer organizing a single auction (corresponding to long-term contracts) to investigate whether a short-term or a long-term contract would be better for the buyer.

We find that a buyer typically favors long-term contracts when supply base is small, since savings from supplier investments are higher as compared to savings obtained through competition. However for larger supply base size the buyer is better-off leveraging fiercer competition (finding a lower-cost supplier in each period) and thus favors short-term contracts. However, the difference in buyer's expected cost from short-term contracts and long-term contracts has a more nuanced dependence on the size of the supply base. This is because the buyer's expected cost in the two-auction setting (short-term contracts) can be non-monotonic in the supply base size, since beyond a certain supply base size the suppliers stop investing, resulting in an increase in the buyer's expected cost. This increase of the buyer's expected cost can inflate buyer's cost in the two-auction setting over its cost in the single-auction case. Thus, the buyer's decision to select a long-term contract (single auction) or short-term contracts (two auctions) critically depends on the supply base size.

Optimally set non-discriminatory reserve prices enable the buyer to lower its expected procurement expenses, but do not affect the validity of our previous results. With discriminatory reserve prices the buyer can better balance the trade-off between benefits from the incumbent supplier's process improvement investment and benefits from second-period price competition between the incumbent supplier and the non-incumbent suppliers. Consistent with our previous findings, the optimal hybrid contract is closer to a long-term contract for smaller supply base sizes, and closer to the short-term contracts for bigger supply base sizes. Also, with an optimal hybrid contract the buyer has sufficient control over its cost (i.e., it avoids non-monotonicity in its expected cost) even when the incumbent supplier stops investing as the supply base size increases.

Interestingly, we find that the expected system cost is typically lower with the short-term contract than with the long-term contract and the difference between the system cost in long-term contract versus short-term contract is increasing in the size of the supply base. This is because in the long-term contract, supplier investment is higher than in the short-term contracts and moreover the expected second-period production cost of supplier is typically higher in long-term contract as compared to short-term contract. Thus from a system perspective the short-term contracts are more efficient than long-term contracts.

Finally, we find that suppliers bid away their second-period gains in both the auction settings. However, in short-term contracts the supplier who did not win the first auction can still win the second-period auction, unlike in the long-term contract. Thus, the supplier can gain a higher surplus, in expectation, through short-term contracts as compared to long-term contract, i.e., a buyer might attract higher supplier participation by giving away short-term contracts as compared to long-term contracts.

We highlight two practical implications of these results. First, it appears that the issues of contract length and supply base size are clearly interrelated. Therefore a buyer should jointly decide on the length of the contract(s) offered to its suppliers along with the size of its supply base. This would allow it to reduce procurement expenses by incentivizing supplier effort in production process improvement along with maintaining supplier competition. Second, our findings strongly suggest that the investment dimension should be incorporated in the joint decision of the contract length and the supply base size. Indeed, in sequential auctions, the non-monotonicity of the buyer's expected cost in the supply base size clearly indicates that neglecting investment can misguide the buyer in making an optimal decision.

In this paper we assumed that investments in new technology made by suppliers have an uncertain impact on their buyer specific production cost, as a result of which their production cost can change from one period to the next. We did not explicitly analyze the amount of investments that these suppliers make. In principle, one can analyze the investments that each supplier would make in equilibrium and then find the resulting distribution of suppliers' production cost for the next period. Such an analysis would be an interesting avenue for future research that builds on this paper.

Finally, one might be further interested in extending the two-auction case by allowing the buyer to split its purchase among more than one supplier, which would allow each of these selected suppliers to invest in process improvement. It would introduce a trade-off between having less suppliers investing more or more suppliers investing less. The buyer can balance the resulting trade-off between supplier competition and production cost improvement by optimally splitting its award amongst the suppliers. This would require investigating mechanism design approach over multiple periods, i.e., investigating dynamic games, which would be a challenging problem to solve.

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Appendix

Characterization of $U_w^s(k_2, n)$

$$U_w^s(k_2,n) = \mathbb{E}_{c_w^s}\mathbb{E}_{c_{1:n-1}^s}[c_{1:n-1}^s - c_w^s | c_{1:n-1}^s \geq c_w^s] \cdot \mathbb{P}(c_{1:n-1}^s \geq c_w^s) - k_2,$$

$$= \int\limits_{x=\underline{c}-\phi(k_2)}^{\bar{c}-\phi(k_2)} \int\limits_{y=max(\underline{c},x)}^{\bar{c}} (y-x) f_{c_w^s}(x) f_{c_{1:n-1}^s}(y) dy dx - k_2,$$

where $f_{c_w^s}$ and $f_{c_{1:n-1}^s}$ are the p.d.f. of c_w^s and $c_{1:n-1}^s$ respectively. Integration by parts on the inner integral gives

$$U_w^s(k_2,n) = \int\limits_{x=\underline{c}-\phi(k_2)}^{\bar{c}-\phi(k_2)} \Big\langle (max(\underline{c},x) - x)\overline{F}_{c_{1:n-1}^s}(max(\underline{c},x)) + \int\limits_{y=max(\underline{c},x)}^{\bar{c}} \overline{F}_{c_{1:n-1}^s}(y) dy \Big\rangle f_{c_w^s}(x) dx - k_2.$$

Since $\int\limits_{x=\underline{c}-\phi(k_2)}^{\bar{c}-\phi(k_2)} (max(\underline{c},x) - x)\overline{F}_{c_{1:n-1}^s}(max(\underline{c},x)) f_{c_w^s}(x) dx = \int\limits_{x=\underline{c}-\phi(k_2)}^{\underline{c}} (\underline{c} - x) f_{c_w^s}(x) dx = \int\limits_{x=\underline{c}-\phi(k_2)}^{\underline{c}} F_{c_w^s}(x) dx$, we have that

$$\begin{aligned} U_w^s(k_2,n) &= \int\limits_{x=\underline{c}-\phi(k_2)}^{\underline{c}} F_{c_w^s}(x) dx + \int\limits_{x=\underline{c}-\phi(k_2)}^{\underline{c}} \int\limits_{y=\underline{c}}^{\bar{c}} \overline{F}_{c_{1:n-1}^s}(y) f_{c_w^s}(x) dy dx \\ &+ \int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \int\limits_{y=x}^{\bar{c}} \overline{F}_{c_{1:n-1}^s}(y) f_{c_w^s}(x) dy dx - k_2. \end{aligned}$$

Integrating $\int\limits_{x=\underline{c}-\phi(k_2)}^{\underline{c}} \int\limits_{y=\underline{c}}^{\bar{c}} \overline{F}_{c^s_{1:n-1}}(y) f_{c^s_w}(x) dy dx$ gives

$$
\begin{aligned}
U^s_w(k_2,n) &= \int\limits_{x=\underline{c}-\phi(k_2)}^{\underline{c}} F_{c^s_w}(x)dx + \int\limits_{y=\underline{c}}^{\bar{c}} \overline{F}_{c^s_{1:n-1}}(y) F_{c^s_w}(\underline{c})dy \\
&+ \int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \int\limits_{y=x}^{\bar{c}-\phi(k_2)} \overline{F}_{c^s_{1:n-1}}(y) f_{c^s_w}(x) dy dx \\
&+ \int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \int\limits_{y=\bar{c}-\phi(k_2)}^{\bar{c}} \overline{F}_{c^s_{1:n-1}}(y) f_{c^s_w}(x) dy dx - k_2. \qquad (21)
\end{aligned}
$$

Integrating $\int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \int\limits_{y=\bar{c}-\phi(k_2)}^{\bar{c}} \overline{F}_{c^s_{1:n-1}}(y) f_{c^s_w}(x) dy dx = \int\limits_{y=\bar{c}-\phi(k_2)}^{\bar{c}} \overline{F}_{c^s_{1:n-1}}(y)dy - \int\limits_{y=\bar{c}-\phi(k_2)}^{\bar{c}} \overline{F}_{c^s_{1:n-1}}(y) F_{c^s_w}(\underline{c})dy$. And integrating by parts

$$
\begin{aligned}
&\int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \int\limits_{y=x}^{\bar{c}-\phi(k_2)} \overline{F}_{c^s_{1:n-1}}(y) f_{c^s_w}(x) dy dx = \\
&\qquad - \int\limits_{y=\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}_{c^s_{1:n-1}}(y) F_{c^s_w}(\underline{c})dy + \int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}_{c^s_{1:n-1}}(x) F_{c^s_w}(x)dx
\end{aligned} \qquad (22)
$$

gives

$$
\begin{aligned}
U^s_w(k_2,n) &= \int\limits_{x=\underline{c}-\phi(k_2)}^{\underline{c}} F_{c^s_w}(x)dx + \int\limits_{y=\bar{c}-\phi(k_2)}^{\bar{c}} \overline{F}_{c^s_{1:n-1}}(y)dy \\
&+ \int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}_{c^s_{1:n-1}}(x) F_{c^s_w}(x)dx - k_2. \qquad (23)
\end{aligned}
$$

Substituting for $F_{c^s_{1:n-1}}(x)$ and $F_{c^s_w}(x)$ gives

$$\begin{aligned} U^s_w(k_2,n) &= \int\limits_{\underline{c}-\phi(k_2)}^{\underline{c}} F(x+\phi(k_2))dx + \int\limits_{\bar{c}-\phi(k_2)}^{\bar{c}} \overline{F}^{n-1}(x)dx \\ &+ \int\limits_{\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}^{n-1}(x)F(x+\phi(k_2))dx - k_2. \end{aligned}$$

Characterization of U^s_l

From Equation (10), we get

$$U^s_l = \int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \int\limits_{y=x}^{\bar{c}-\phi(k_2)} (y-x)f_{\zeta^s}(y)f_{c^s_i}(x)dydx.$$

Integrating by parts $\int\limits_{y=x}^{\bar{c}-\phi(k_2)} (y-x)f_{\zeta^s}(y)dy$, we get

$$U^s_l = \int\limits_{x=\underline{c}}^{\bar{c}-\phi(k_2)} \int\limits_{y=x}^{\bar{c}-\phi(k_2)} \overline{F}_{\zeta^s}(y)f_{c^s_i}(x)dydx.$$

Further integration by parts gives

$$U^s_l = \int\limits_{\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}_{\zeta^s}(x)F_{c^s_i}(x)dx$$

Substituting $\overline{F}_{\zeta^s}(x) = \overline{F}^{n-2}(x)\overline{F}(x+\phi(k_2))$ gives

$$U^s_l = \int\limits_{\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}^{n-2}(x)F(x)\overline{F}(x+\phi(k_2))dx. \tag{24}$$

Proofs

Proof of Lemma 1 Lemma 1 is verified if $\frac{d\mathbb{E}c_{2:n}}{dn} \leq 0$, which is true if the expression inside the integral of Equation (2) (let us denote it $v(x)$) decreases in n:

$$\begin{aligned}
\frac{dv(x)}{dn} &= \frac{d\Big\langle \overline{F}^{n-1}(x)\Big\langle nF(x)+\overline{F}(x)\Big\rangle\Big\rangle}{dn} \\
&= \overline{F}^{n-1}(x)F(x) + (nF(x)+\overline{F}(x))\overline{F}^{n-1}(x)\ln(\overline{F}(x)) \\
&= \overline{F}^{n-1}(x)\Big\langle F(x) + (n-1)F(x)\ln(\overline{F}(x)) + \ln(\overline{F}(x))\Big\rangle.
\end{aligned}$$

Let $z(x) \equiv F(x) + \ln(\overline{F}(x))$. Then $z(\underline{c}) = 0$ and $dz(x)/dx = f(x) - f(x)/\overline{F}(x) \leq 0$ (since $\overline{F}(x) \leq 1$). Therefore $F(x) + \ln(\overline{F}(x)) \leq 0$ and hence $dv(x)/dn \leq 0$ (because $\ln(\overline{F}(x)) \leq 0$), such that $d\mathbb{E}c_{2:n}/dn \leq 0$. In Equation (3), $\mathbb{E}c^s$ is independent of n and therefore the difference in buyer's expected cost between the single-auction and two-auction case increases in n. Morevoer, at $n \to \infty$, $\mathbb{E}c^s - \mathbb{E}c_{2:n} \geq 0$. Hence, there exists a threshold n beyond which expected cost in single auction would be greater than expected cost in two-auction case.

Proof of Proposition 1 The winner of the first auction invests k_2^* such that it maximizes $U_w^s(k_2, n)$. From Equation (6), we can characterize $\frac{\partial U_w^s(k_2,n)}{\partial k_2}$ as

$$\begin{aligned}
\frac{\partial U_w^s(k_2,n)}{\partial k_2} &= -F(\underline{c})(-\frac{d\phi(k_2)}{dk_2}) + \int\limits_{\underline{c}-\phi(k_2)}^{\underline{c}} \frac{dF(x+\phi(k_2))}{dk_2}dx - \overline{F}^{n-1}(\bar{c}-\phi(k_2))F(\bar{c})\frac{d\phi(k_2)}{dk_2} \\
&+ \int\limits_{\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}^{n-1}(x)\frac{dF(x+\phi(k_2))}{dk_2}dx + \overline{F}^{n-1}(\bar{c}-\phi(k_2))\frac{d\phi(k_2)}{dk_2} - 1 \\
&= \frac{d\phi(k_2)}{dk_2}\cdot\Big\langle F(\underline{c}+\phi(k_2)) + \int\limits_{\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}^{n-1}(x)f(x+\phi(k_2))dx\Big\rangle - 1. \qquad (25)
\end{aligned}$$

Any interior solution of k_2^* will be characterized by

$$\frac{\partial U_w^s(k_2^*(n), n)}{\partial k_2} = 0. \tag{26}$$

Implicitly differentiating Equation (26) with respect to an $n \in \mathbf{R}$ gives:

$$\frac{\partial \langle \frac{\partial U_w^s(k_2^*(n),n)}{\partial k_2} \rangle}{\partial n} = \frac{\partial^2 U_w^s(k_2^*(n), n)}{\partial k_2^2} \frac{dk_2^*(n)}{dn} + \frac{\partial^2 U_w^s(k_2^*(n), n)}{\partial k_2 \partial n} = 0.$$

We can then characterize

$$\frac{dk_2^*(n)}{dn} = \frac{-\frac{\partial^2 U_w^s(k_2^*(n),n)}{\partial k_2 \partial n}}{\frac{\partial^2 U_w^s(k_2^*(n),n)}{\partial k_2^2}}.$$

From Equation (25) we know that $\frac{\partial^2 U_w^s(k_2,n)}{\partial k_2 \partial n} \leq 0$. Moreover, at k_2^* we will always have $\frac{\partial^2 U_w^s(k_2^*(n),n)}{\partial k_2^2} \leq 0$. Therefore $\frac{dk_2^*(n)}{dn} < 0$ at any interior solution of k_2^*. Since $\frac{\partial^2 U_w^s(k_2,n)}{\partial k_2 \partial n} \leq 0$, increasing n can not increase k_2^* when $k_2^* = 0$. Hence k_2^* is decreasing in n.

Proof of Theorem 1 The first two conditions of Theorem 1 ensure that $U_w^s(0, m)$ is decreasing and convex in k_2 at $k_2 = 0$, $\forall m \geq m^t$. The third condition implies that $U_w^s(k_2, m)$ has at most two local optima for all $m \geq m^t$. Let $k_2^{min}(m)$ and $k_2^{max}(m)$ respectively denote the local minimum and the local maximum of $U_w^s(k_2, m)$. Indeed, $k_2^{min}(m) \leq k_2^{max}(m)$.

From Equation (25) we know that $\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2 \partial m} < 0$. Therefore, if $U_w^s(k_2, m^t)$ has no local optimum, or if the local maximum k_2^{max} is such that $U_w^s(k_2^{max}, m^t) < U_w^s(0, m^t)$, then $k_2^*(m) = 0$ $\forall m \geq m^t$.

Also since $\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2 \partial m} < 0$, for $U_w^s(k_2^{max}, m^t) > U_w^s(0, m^t)$, $k_2^{min}(m)$ is increasing in m and $k_2^{max}(m)$ is decreasing in m. Thus $k_2^{max}(m)$ is lower bounded by $k_2^{min}(m^t)$. Moreover, since $k_2^*(m)$ is decreasing in m (from

Proposition 1), condition (4) can only get satisfied if k_2^* discontinuously decreases to 0 as m increases.

Proof of Proposition 2 For an $m \in R$ and uniformly distributed costs we can characterize $U_w^s(k_2, m)$ in Equation (6) as

$$\begin{aligned}
U_w^s(k_2,m) &= \int_{\underline{c}-\phi(k_2)}^{\underline{c}} \frac{x-\underline{c}+\phi(k_2)}{\bar{c}-\underline{c}}dx + \int_{\underline{c}}^{\bar{c}-\phi(k_2)} \Big(\frac{\bar{c}-x}{\bar{c}-\underline{c}}\Big)^{m-1}\Big(\frac{x-\underline{c}+\phi(k_2)}{\bar{c}-\underline{c}}\Big)dx \\
&+ \int_{\bar{c}-\phi(k_2)}^{\bar{c}} \Big(\frac{\bar{c}-x}{\bar{c}-\underline{c}}\Big)^{m-1}dx - k_2 \\
&= \frac{\phi(k_2)(\phi(k_2)-\underline{c})}{\bar{c}-\underline{c}} + \Big[\frac{2\underline{c}\phi(k_2)-\phi(k_2)^2}{2(\bar{c}-\underline{c})}\Big] - \frac{\phi(k_2)^m}{m(\bar{c}-\underline{c})^{m-1}} + \frac{\phi(k_2)}{m} \\
&- \frac{\phi(k_2)^{m+1}}{m(m+1)(\bar{c}-\underline{c})^m} + \frac{(\bar{c}-\underline{c})}{m(m+1)} + \frac{\phi(k_2)^m}{m(\bar{c}-\underline{c})^{m-1}} - k_2 \\
&= \frac{(\phi(k_2))^2}{2(\bar{c}-\underline{c})} + \frac{\phi(k_2)}{m} - \frac{\phi(k_2)^{m+1}}{m(m+1)(\bar{c}-\underline{c})^m} + \frac{(\bar{c}-\underline{c})}{m(m+1)} - k_2. \qquad (27)
\end{aligned}$$

Taking derivative of $U_w^s(k_2, m)$ gives

$$\frac{\partial U_w^s(k_2,m)}{\partial k_2} = \frac{d\phi(k_2)}{dk_2}\Big\langle \frac{\phi(k_2)}{\bar{c}-\underline{c}} + \frac{1}{m}\Big(1-\Big(\frac{\phi(k_2)}{\bar{c}-\underline{c}}\Big)^m\Big)\Big\rangle - 1,$$

and

$$\begin{aligned}
\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2^2} &= \frac{d^2\phi(k_2)}{dk_2^2}\Big\langle \frac{\phi(k_2)}{\bar{c}-\underline{c}} + \frac{1}{m}\Big(1-\Big(\frac{\phi(k_2)}{\bar{c}-\underline{c}}\Big)^m\Big)\Big\rangle \\
&+ \Big(\frac{d\phi(k_2)}{dk_2}\Big)^2\Big\langle \frac{1}{\bar{c}-\underline{c}} - \frac{(\phi(k_2))^{m-1}}{(\bar{c}-\underline{c})^m}\Big\rangle.
\end{aligned}$$

Substituting for $\phi(k) = \phi_{max}(1-e^{-\lambda k})$, we get $\frac{\partial U_w^s(0,m)}{\partial k_2} = \frac{\phi_{max}\lambda}{m} - 1$ and $\frac{\partial^2 U_w^s(0,m)}{\partial k_2^2} = \frac{-\phi_{max}\lambda^2}{m} + \frac{(\phi_{max}\lambda)^2}{\bar{c}-\underline{c}}$. Thus conditions (1) and (2) of Theorem 1 are satisfied for $m^t \geq \max(\lambda\phi_{max}, \frac{\bar{c}-\underline{c}}{\phi_{max}})$. To show condition (3) of Theorem 1 we introduce $\phi(k) = \phi_{max}(1-e^{-\lambda k})$ into $\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2^2}$:

$$\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2^2} = \lambda^2 \phi_{max} e^{-\lambda k_2} \Big\langle \frac{\phi_{max}(2e^{-\lambda k_2}-1)}{\bar{c}-\underline{c}} - \frac{1}{m} + \frac{\phi_{max}^m (1-e^{-\lambda k_2})^{m-1}}{m(\bar{c}-\underline{c})^m} \Big\langle 1-(m+1)e^{-\lambda k_2} \Big\rangle \Big\rangle.$$

Define $h(k_2,m) \equiv \frac{\phi_{max}(2e^{-\lambda k_2}-1)}{\bar{c}-\underline{c}} - \frac{1}{m} + \frac{\phi_{max}^m (1-e^{-\lambda k_2})^{m-1}}{m(\bar{c}-\underline{c})^m} \Big\langle 1-(m+1)e^{-\lambda k_2} \Big\rangle$. We can then characterize $\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2^2} = \lambda^2 \phi_{max} e^{-\lambda k_2} h(k_2,m)$. Thus, if $h(k_2,m)$ is decreasing in k_2 then $\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2^2} = 0$ can have at most one solution.

$$\frac{\partial h(k_2,m)}{\partial k_2} = \frac{\lambda \phi_{max} e^{-\lambda k_2}}{\bar{c}-\underline{c}} \Big\langle -2 + (1-e^{-\lambda k_2})^{m-2} \Big(\frac{\phi_{max}}{\bar{c}-\underline{c}}\Big)^{m-1} \Big\langle 2-(m+1)e^{-\lambda k_2} \Big\rangle \Big\rangle.$$

Since $(1-e^{-\lambda k_2})^{m-2} \leq 1$; $\frac{\partial h(k_2,m)}{\partial k_2} \leq 0$ if $\frac{\phi_{max}}{\bar{c}-\underline{c}} \leq 1$. Moreover, $h(\infty,m) < 0$ for $\frac{\phi_{max}}{\bar{c}-\underline{c}} \leq 1$, which implies that $\frac{\partial^2 U_w^s(k_2,m)}{\partial k_2^2} = 0$ has a unique solution (since $\frac{\partial^2 U_w^s(0,m)}{\partial k_2^2} > 0$). Thus condition (3) of Theorem 1 gets satisfied for $\frac{\phi_{max}}{\bar{c}-\underline{c}} \leq 1$.

Finally we determine when condition (4) of Theorem 1 is true. For $\frac{\phi_{max}}{\bar{c}-\underline{c}} \leq 1$ we get

$$\frac{\partial U_w^s(k_2,+\infty)}{\partial k_2} = \frac{d\phi(k_2)}{dk_2} \cdot \frac{\phi(k_2)}{\bar{c}-\underline{c}} - 1 = \lambda \phi_{max} e^{-\lambda k} \frac{\phi_{max}(1-e^{-\lambda k})}{\bar{c}-\underline{c}} - 1.$$

For $\lambda \phi_{max} \leq (\bar{c}-\underline{c})/\phi_{max}$, we get that $\frac{\partial U_w^s(k_2,+\infty)}{\partial k_2} \leq 0$ and therefore $k_2^*(\infty) = 0$. Thus we see that all conditions of Theorem 1 are satisfied if: $m^t \geq \max(\lambda \phi_{max}, \frac{\bar{c}-\underline{c}}{\phi_{max}})$; $\frac{\phi_{max}}{\bar{c}-\underline{c}} \leq 1$ and if $\lambda \phi_{max} \leq (\bar{c}-\underline{c})/\phi_{max}$. Since $m^t \geq 2$, conditions of Theorem 1 are satisfied if $2 \geq (\bar{c}-\underline{c})/\phi_{max}$; $\lambda \phi_{max} \leq (\bar{c}-\underline{c})/\phi_{max}$ and $\frac{\phi_{max}}{\bar{c}-\underline{c}} \leq 1$. Or equivalently conditions of Theorem 1 are satisfied if $2 \geq \frac{\bar{c}-\underline{c}}{\phi_{max}} \geq 1$ and $\lambda \phi_{max} \leq \frac{\bar{c}-\underline{c}}{\phi_{max}}$.

Proof of Proposition 3: To investigate the impact of cost spread $\bar{c}-\underline{c}$ on the optimal investment k_2^*, we define $U_w^s(k_2, \bar{c}-\underline{c})$ as the incumbent supplier's expected utility for the second-period. From Equation (27), we can characterize $U^s_w(k_2, \bar{c}-\underline{c})$ for uniformly distributed cost as

$$U^s_w(k_2, \bar{c}-\underline{c}) = \frac{(\phi(k_2))^2}{2(\bar{c}-\underline{c})} + \frac{\phi(k_2)}{n} - \frac{\phi(k_2)^{n+1}}{n(n+1)(\bar{c}-\underline{c})^n} + \frac{(\bar{c}-\underline{c})}{n(n+1)} - k_2$$

Taking the first order condition of $U^s_w(k_2, \bar{c}-\underline{c})$ allows us to characterize the optimal investment $k_2^*(\bar{c}-\underline{c})$ through the following Equation:

$$\frac{\partial U^s_w(k_2, \bar{c}-\underline{c})}{\partial k_2} = \frac{d\phi(k_2)}{dk_2}\Big\langle \frac{\phi(k_2)}{\bar{c}-\underline{c}} + \frac{1}{n}\Big(1 - \Big(\frac{\phi(k_2)}{\bar{c}-\underline{c}}\Big)^n\Big)\Big\rangle - 1 = 0.$$

Implicitly differentiating the first order condition with respect to $\bar{c}-\underline{c}$ gives

$$\frac{\partial\langle\frac{\partial U^s_w(k_2^*(\bar{c}-\underline{c}), \bar{c}-\underline{c})}{\partial k_2}\rangle}{\partial(\bar{c}-\underline{c})} = \frac{\partial^2 U^s_w(k_2, \bar{c}-\underline{c})}{\partial k_2^2}\frac{dk_2^*(\bar{c}-\underline{c})}{d(\bar{c}-\underline{c})} + \frac{\partial^2 U^s_w(k_2^*(\bar{c}-\underline{c}), \bar{c}-\underline{c})}{\partial k_2 \partial(\bar{c}-\underline{c})} = 0, \tag{28}$$

i.e.,

$$\frac{dk_2^*(\bar{c}-\underline{c})}{d(\bar{c}-\underline{c})} = \frac{-\frac{\partial^2 U^s_w(k_2^*(\bar{c}-\underline{c}), \bar{c}-\underline{c})}{\partial k_2 \partial(\bar{c}-\underline{c})}}{\frac{\partial^2 U^s_w(k_2^*(\bar{c}-\underline{c}), \bar{c}-\underline{c})}{\partial k_2^2}}. \tag{29}$$

From the first order condition we find that, at optimum, $\frac{\partial^2 U^s_w(k_2^*(\bar{c}-\underline{c}), \bar{c}-\underline{c})}{\partial k_2 \partial(\bar{c}-\underline{c})} = -\frac{d\phi(k_2^*)}{dk_2} \cdot \frac{\phi(k_2^*)}{(\bar{c}-\underline{c})^2}\Big\langle 1 - \Big(\frac{\phi(k_2^*)}{\bar{c}-\underline{c}}\Big)^{n-1}\Big\rangle \leq 0$ if $\frac{\phi(k_2^*)}{\bar{c}-\underline{c}} \leq 1$. Moreover, by definition of a maximum $\frac{\partial^2 U^s_w(k_2^*(\bar{c}-\underline{c}), \bar{c}-\underline{c})}{\partial k_2^2} < 0$. Thus $\frac{dk_2^*(\bar{c}-\underline{c})}{d(\bar{c}-\underline{c})} \leq 0$ if $\frac{\phi(k_2^*)}{\bar{c}-\underline{c}} \leq 1$. Since $\phi(k) \leq \bar{c}-\underline{c}$, $\forall k$, we have that $\frac{dk_2^*(\bar{c}-\underline{c})}{d(\bar{c}-\underline{c})} \leq 0$.

Proof of Proposition 4 In the single-auction case, optimal investment k_1^* is determined through the following first order condition: $\frac{d\phi(k_1)}{dk_1} = 1$. Since $\phi(k) - k$ is concave in k, there is a unique global maximum. In the two-auction case, the first order condition for optimal investment is $dU^s_w(k_2, n)/dk_2 = 0$, which can be characterized from

Equation (6) as:

$$\frac{d\phi(k_2)}{dk_2} \cdot \left\langle F(\underline{c} + \phi(k_2)) + \int_{\underline{c}}^{\bar{c}-\phi(k_2)} \overline{F}^{n-1}(x) f(x + \phi(k_2)) dx \right\rangle = 1.$$

Because $U_w^s(k_2, n)$ is not necessarily concave or convex, this FOC could give several local optima. We want to show that none of these potential local maxima can be higher than the optimal investment from the single-auction setting. For this, we first note that

$$F(\underline{c} + \phi(k_2)) + \int_{\underline{c}}^{\bar{c}-\phi(k)} \overline{F}^{n-1}(x) f(x + \phi(k)) dx$$
$$\leq \int_{\underline{c}-\phi(k)}^{\underline{c}} f(x + \phi(k)) dx + \int_{\underline{c}}^{\bar{c}-\phi(k)} f(x + \phi(k)) dx = 1.$$

Therefore $\left\langle F(\underline{c} + \phi(k)) + \int_{\underline{c}}^{\bar{c}-\phi(k)} \overline{F}^{n-1}(x) f(x + \phi(k)) dx \right\rangle \leq 1$ and the optimal k_2^* should satisfy $\frac{d\phi(k_2^*)}{dk_2} \geq 1$. However, optimal k_1^* satisfies $\frac{d\phi(k_1^*)}{dk_1} = 1$. Thus $\frac{d\phi(k_2^*)}{dk_2} \geq \frac{d\phi(k_1^*)}{dk_1}$. Since $\phi(k)$ is increasing and concave in k, this implies that $k_1^* \geq k_2^*$. Finally, from Proposition 1 we know that k_2^* decreases in n, whereas k_1^* is independent on n. Thus regardless of the supply base size, $k_1^* \geq k_2^*$.

Proof of Lemma 2 We denote by b_i^f the per-unit bid of supplier i in the first period. We assume that the other suppliers $j \neq i$ follow an increasing and continuous bidding strategy $b_j^f = \beta(c_j^f)$. We can then characterize supplier i's total (over the two periods) expected profit as

$$\pi_i = \begin{cases} U_w^s(k_2, n) + b_{1:n-1}^f - c_i^f & \text{if } b_i^f < b_{1:n-1}^f \\ U_l^s & \text{if } b_i^f > b_{1:n-1}^f, \end{cases}$$

where $b^f_{1:n-1}$ represents the lowest bid amongst the $n-1$ other suppliers in the first auction. Denote by $c^f_{1:n-1}$ the first-period lowest cost amongst $n-1$ other suppliers, and denote by $f_{c^f_{1:n-1}}(x)$ the density of $c^f_{1:n-1}$, we can characterize supplier i's expected profit as

$$\begin{aligned}
\mathbb{E}\pi_i &= \overline{F}_{c^f_{1:n-1}}(\beta^{-1}(b^f_i))\Big(U^s_w(k_2,n)+\mathbb{E}\Big(\beta(c^f_{1:n-1})|\beta(c^f_{1:n-1})>b^f_i\Big)-c^f_i\Big)\\
&+ F_{c^f_{1:n-1}}(\beta^{-1}(b^f_i))U^s_l\\
&= \overline{F}_{c^f_{1:n-1}}(\beta^{-1}(b^f_i))\Big(U^s_w(k_2,n)-c^f_i\Big)\\
&+ \int\limits_{\beta^{-1}(b^f_i)}^{\bar{c}} \beta(x)f_{c^f_{1:n-1}}(x)dx+F_{c^f_{1:n-1}}(\beta^{-1}(b^f_i))U^s_l.
\end{aligned}$$

Differentiating the above with respect to b^f_i and equating it to 0 gives

$$\frac{d\mathbb{E}\pi_i}{db^f_i}=f_{c^f_{1:n-1}}(\beta^{-1}(b^f_i))\frac{d\beta^{-1}(b^f_i)}{db^f_i}\Big(-\beta(\beta^{-1}(b^f_i))+c^f_i-\delta\Big)=0,$$

where $\delta=U^s_w(k_2,n)-U^s_l$. Assuming that supplier i also follows the similar bidding strategy $\beta(c^f_i)=b^f$, allows us to characterize β from the above first order condition as

$$f_{c^f_{1:n-1}}(c^f_i)\frac{1}{d\beta(c^f_i)/dc^f_i}\Big(-\beta(c^f_i)+c^f_i-\delta\Big)=0,$$

which implies that $\beta_{double}(c^f_i)=c^f_i-\delta$. Note that β is increasing in c^f_i since δ does not depend on c^f_i. We further need to check whether this strategy forms an equilibrium, i.e., maximizes supplier i's surplus. Let supplier i misrepresent itself as a supplier with cost z, then its expected surplus can be characterized as :

$$\begin{aligned}
\mathbb{E}\pi_i(\beta_{double}(z), c_i^f) &= \overline{F}_{c^f_{1:n-1}}(z)\Big(U_w^s(k_2,n) - c_i^f\Big) \\
&+ \int_z^{\bar{c}} \Big(x + U_l^s - U_w^s(k_2,n)\Big) f_{c^f_{1:n-1}}(x)dx + F_{c^f_{1:n-1}}(z)U_l^s \\
&= U_l^s + \overline{F}_{c^f_{1:n-1}}(z)\Big(z - c_i^f\Big) + \int_z^{\bar{c}} \overline{F}_{c^f_{1:n-1}}(x)dx.
\end{aligned}$$

Since $\mathbb{E}\pi_i(\beta^*_{double}(z), c_i^f) - \mathbb{E}\pi_i(\beta^*_{double}(c_i^f), c_i^f) = \overline{F}_{c^f_{1:n-1}}(z)\Big(z - c_i^f\Big) + \int_z^{\bar{c}} \overline{F}_{c^f_{1:n-1}}(x)dx - \int_c^{\bar{c}} \overline{F}_{c^f_{1:n-1}}(x)dx \leq 0$ for all z implies that $\beta^*_{double}(c_i^f) = c_i^f - \delta$ is indeed an equilibrium bidding strategy.

Proof of Proposition 5 In the single-auction case, supplier i's expected utility is given by

$$\mathbb{E}U_{single} = \mathbb{E}_{b_{1:n-1}}\Big[b_{1:n-1} - c_i^f - \mathbb{E}c_w^s - k_1^* | b_{1:n-1} \geq b_i\Big] \cdot \mathbb{P}(b_{1:n-1} \geq b_i).$$

Since suppliers bid according to Equation (8), supplier i's expected utility can be characterized as

$$\mathbb{E}U_{single} = \mathbb{E}_{c^f_{1:n-1}}\Big[c^f_{1:n-1} - c_i^f | c^f_{1:n-1} \geq c_i^f\Big] \cdot \mathbb{P}(c^f_{1:n-1} \geq c_i^f).$$

Similarly, in the two-auction case, supplier i's expected utility before first auction is

$$\begin{aligned}
\mathbb{E}U_{double} &= \mathbb{E}_{b^f_{1:n-1}}\Big[U_w^s(k_2,n) + b^f_{1:n-1} - c_i^f | b^f_{1:n-1} \geq b_i^f\Big] \cdot \mathbb{P}(b^f_{1:n-1} \geq b_i^f) \\
&+ U_l^s \cdot \mathbb{P}(b^f_{1:n-1} \leq b_i^f) \\
&= \mathbb{E}_{b^f_{1:n-1}}\Big[U_w^s(k_2,n) - U_l^s + b^f_{1:n-1} - c_i^f | b^f_{1:n-1} \geq b_i^f\Big] \cdot \mathbb{P}(b^f_{1:n-1} \geq b_i^f) + U_l^s.
\end{aligned}$$

Since $\delta = U_w^s(k_2, n) - U_l^s$ and from Lemma 2 we know the equilibrium bid of each supplier as $\beta^*_{double}(c_i^f) = b_i^f = c_i^f - \delta$. Thus supplier i's expected utility can be characterized as

$$\mathbb{E}U_{double} = \mathbb{E}_{c^f_{1:n-1}}\left[c^f_{1:n-1} - c_i^f | c^f_{1:n-1} \geq c_i^f\right] \cdot \mathbb{P}(c^f_{1:n-1} \geq c_i^f) + U_l^s.$$

Since $U_l^s \geq 0$, it follows that $\mathbb{E}U_{double} \geq \mathbb{E}U_{single}$.

4. Chapter 3 - Cost of information sharing in group purchasing

4.1 Foreword of Chapter 3

The third chapter of this dissertation is entitled *"Cost of information sharing under group purchasing"*, and it is a joint work with W. Peng, Pr. A. Chaturvedi and Pr. P. Chevalier. This chapter focuses on the information leakage that would be unavoidable when firms join in buying groups, in order to obtain a lower per-unit purchasing price from a common supplier. More precisely, we determine under which conditions the cost benefits of group purchasing would outweigh the cost of disclosing information to a competitor. For this, we use an analytical model considering Cournot competition.

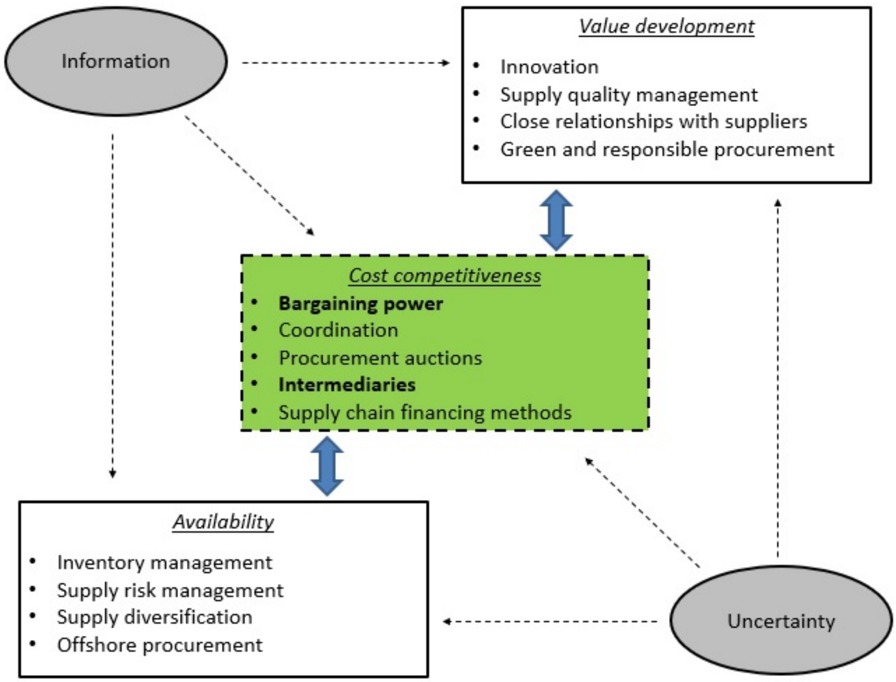

Figure 23: Positioning of Chapter 3 according to the framework presented in Figure 2.

This chapter pertains principally to the literature dealing with procurement cost reductions. Namely, it examines the incentives for buyers engaged in horizontal competition to jointly purchase a component from a common supplier, as a mean to increase their bargaining power and hence negotiate down the per-unit purchasing price received from this supplier. Although we do consider group purchasing organizations in this project, this work also shares some common grounds with the literature on supply chain intermediaries, since the logic of the paper could be adapted to group purchasing organizations. In addition, this project deals with both uncertainty and information management. Namely, it takes into account two types of uncertainties that can be present in competitive markets, and considers that through group purchasing, the firms reduce the uncertainty by disclosing information to each other. Therefore, both uncertainty and information clearly affect the rival firms' decision on jointly purchasing or not. Finally, in the introduction of this dissertation, we have discussed the benefits from vertically sharing information along the supply chain, in terms of inventory decisions and supply chain coordination. This chapter focuses rather on horizontal information sharing and its implications on horizontal competition, which, outside of group purchasing, is not related to the procurement literature. However, horizontal information sharing is usually studied to find new cost reduction opportunities. These pieces of information are represented in Figure 23.

Group purchasing across rival firms suits well the current business environment for two principal reasons. First, the increasingly competitive environment pushes firms to search for original means of reducing costs. While cooperating with a rival might have been philosophically unacceptable in the past, it has almost become a common practice in several supply chain activities (inventories, logistics, production, etc...). This might have been facilitated by the outsourcing trend, which has trivialized the reliance on outside partners' capabilities. Second, as the environment allows nowadays any firm to work with the worldwide most efficient suppliers, many firms actually have the same suppliers, especially when few suppliers can deliver a certain component. For example, competing giants in the hi-tech and automotive sectors have plenty of common suppliers (*a fortiori* if they diversify their supply). This context makes more likely the creation of buying groups across rival firms.

Deciding whether to jointly purchase with a rival would follow a highly strategic decision. It implies to estimate anticipatively the impact of sensitive information leakage across firms on the outcome of horizontal competition, and to compare this with the cost benefits derived from group purchasing. In some situations, rival firms would prefer to purchase jointly, whereas in other situations they would not. Hence, it is not trivial whether on average, they would be willing to disclose strategic information to their rival.

Cost of Information Sharing Under Group Purchasing

G. Merckx • W. Peng • A. Chaturvedi • P. Chevalier

While group purchasing amongst competing OEMs enables these to obtain rebates from the supplier, it also requires regular interactions between the OEMs, which result in disclosure of private information such that OEMs might prefer individual purchasing to conceal their private information. This paper investigates how information sharing dimension affects OEMs' motivations towards group purchasing, specifically in industries characterized by market demand and technology level uncertainties. Under Cournot competition, we find that group purchasing is preferred by OEMs when product technology strongly affects market demand, and that preference for group purchasing would depend on product substitutability, market demand variability and supplier rebate when influence of the product technology is low. We further find that group purchasing can benefit both the OEMs and the consumers.

4.2 Introduction

In order to reduce their procurement cost competing Original Equipment Manufacturers (OEMs) might collaborate to jointly procure components from a common supplier through a *group purchasing agreement.* For example, BMW and Daimler have jointly purchased tyres and seat frames for several years now, and consider procuring further items together (Reuters, 2017). Similarly, nine Chinese TV makers have been together spending around 5 billion dollars each year since 2009 in jointly ordering flat screens from Taiwanese producers (ChinaDaily, 2011). Although the input cost reduction aspect of group purchasing (hereafter referred to as GP) has been widely documented in the extant literature, whether or when should rival OEMs prefer GP agreements over the traditional individual purchase order (hereafter referred to as IP) from their respective supplier/s remains debatable. Chen and Roma (2011) argue that one reason why competing OEMs might prefer IP over GP agreements could be due to order size asymmetry across OEMs. Since per-unit procurement costs are typically decreasing in the quantity ordered, an OEM ordering more units would actually subsidize its competitor's purchase price through GP, and hence erode its own competitive advantage. Moreover, under GP the OEMs have to coordinate upfront in order to negotiate as a single buyer with the supplier, For instance OEMs would have to coordinate on a joint order quantity that they would place to the supplier. Such coordination between OEMs would implicitly involve disclosure of sensitive market information, which they might not prefer to reveal to each other. Thus even though GP would give lower procurement cost to the competing OEMs it might also involve unavoidable disclosure of private information, which makes it unclear why (or when) competing OEMs might want to enter into GP agreements. It is this question that we try to answer in this paper by addressing the trade-off between lower procurement cost and information disclosure when entering into GP agreement.

Actually, whether information disclosure is always detrimental to competing OEMs' profitability is far from being trivial. Economics literature has shown that competing firms' incentives to disclose private information critically depends on the type of information exchanged and on the type of competition. For instance, Clarke (1983), Vives (1984) and Gal-Or (1985) have shown that firms sharing private information about their common demand estimates correlates their strategies (i.e., the quantities that they bring in the market) which in turn hurts their expected profits when they are competing à la Cournot but not necessarily under Bertrand competition. However, Fried (1984) and Shapiro (1986) have shown that firms sharing private information on production costs does not necessarily correlate their strategies and hence could in fact increase their expected profits.

Besides being privately informed on common demand, OEMs might also be better informed about the technology level of their own product as compared to the rival's product before these products are brought out into the market. Information on technology level of product includes knowledge on the extent to which a new product has been upgraded or if the new product belongs to a new generation. Upgrades to existing products or whether the product belongs to a new generation is dependent on R&D programs whose eventual success or failure is known to the undertaking firm and not to the rival firm. Hence the technology level of product, prior to its launch, is private information of the firm. Evidently, the product's technology level would be an important determinant of its eventual market demand. In markets that see frequent introduction of new products, e.g. electronics, the competing OEMs might simultaneously (or within relatively short interval) bring out their respective products thus resulting in the demand for their products not only being influenced by their own product's technology level but also by the competing product's technology level. If these OEMs enter into a GP agreement prior to product launch for pooling their order quantities on a common item, then these firms would not only be communicating (advertently or inadvertently) their information about *common market demand* but also their private information on the *impact* that their proprietary product technology would have on the market demand. Since firms typically decide on GP agreement and consequentially their order quantities before introducing their product to the market, therefore it is natural that decision to enter into a GP agreement should be assessed through the lens of Cournot competition. As discussed above disclosing common market demand information would usually hurt OEMs' expected profits when they are competing à la Cournot. However, the impact on OEMs profitability from disclosing information about product technology has never been studied.

Built on these observations, our objective is threefold: (1) independent of procurement cost advantage we first investigate the economics of information sharing (on both market demand and technology level) and characterize the conditions under which OEMs would be penalized from information disclosure inherent to GP. (2) For situations in which OEMs are better off by concealing information, we study whether the purchasing cost advantage derived from GP can offset their cost of disclosing information. (3) We investigate the impact of GP agreements on consumer surplus to characterize situations under which GP agreements would benefit both the OEMs and the consumers. This last point is important in determining when would GP agreements be acceptable by both competing OEMs and by anti-competitive regulations.

To address the above issues we investigate a stylized three-period duopoly model with Cournot competition. In the third (last) period both OEMs realize their market demand, which we model through their respective inverse demand functions that are linked by a common market demand parameter and by substitutability between their respective products. In the second period both OEMs observe their private signals on the common market demand and observe their realized technology level (which in turn influences their products demand). The OEMs then disclose their signals to each other if they have entered into a GP agreement in period 1 and then decide individually on their respective order quantity which they then pool to jointly procure from a common supplier. If they have not agreed on GP then they decide their order quantity individually without disclosing their signal (and without knowing the other's order quantity) and procure their respective quantities at a higher per-unit cost as compared to the GP agreement. In the first period both the OEMs decide whether they want to enter into a GP agreement or not (with the default strategy being IP).

We find that when technology level is the only source of private information then the OEMs always prefer to share their information with each other. However, they prefer to conceal their private information on market demand uncertainty when it is the only source of private information and as long as product substitutability is sufficiently high. When competing OEMs' information on both technology level and market demand are private then getting into GP agreements would require them to reveal their information on both technology and market to each other. We find that sharing or not sharing technology level and market demand information can be favored, depending on product substitutability, market demand variability, signal accuracy, as well as market impact of technology. This latter factor is crucial in determining OEMs' purchasing strategy when purchase cost reduction in GP is taken into consideration. If product technology has a strong market impact, GP is always beneficial for the OEMs, whereas for a weaker market impact of technology, GP is favored over IP only if product substitutability is low or if market demand variability is limited as compared to the reduction in purchase cost in GP. We further find that, if GP does not give any cost reduction compared to IP then OEMs and consumers never benefit simultaneously from the information revelation inherent in GP agreements, when only market demand or technology level is the source of private information. However, when both are sources of private information then there always exists situations in which GP would be preferred by both OEMs and consumers. These situations become more frequent as cost reduction obtained through GP increases, suggesting that OEMs pass on a part of this cost reduction from their supplier to the consumers.

The remainder of the paper is organized as follows. In Section 4.3, we review the literature dealing with information sharing and GP. We study the IP strategy in Section 4.4, the GP strategy in Section 4.5 and compare those strategies in Section 4.6. Finally, we discuss the consumer welfare implications in Section 4.7 and present our concluding remarks in Section 4.8. All the relevant proofs are present in the Appendix.

4.3 Literature Review

This paper is principally related to two broad streams of literature dealing with to 1) information sharing and to 2) group purchasing. Economics literature has investigated the benefits and disadvantages of information sharing between competing firms. In case of Cournot competition is considered, Clarke (1983), Vives (1984), Gal-Or (1985) and Li (1985) show that not sharing information is a dominant strategy if firms are symmetrically informed about common uncertain demand intercept and if goods are close substitutes. In contrast, Li (1985), Fried (1984) and Shapiro (1986) find that sharing information is a dominant strategy if firms possess private information about their own cost. The rationale is that releasing firm-specific information makes firms' decisions less correlated, which has a positive impact on firms' profits, unlike releasing common market information, which makes firms' decisions more correlated. These conclusions are reversed under Bertrand competition (Vives, 1984; Gal-Or, 1985). Our paper investigates information sharing under Cournot competition about both common market, i.e. the maximum price that the market is willing to accept, and about a firm-specific technology, i.e. OEM's information on the price sensitivity of its product.

GP agreements first emerged in public entities, like hospitals or schools, between which there is no competition. In that case, GP mostly lowers purchasing expenses with limited disadvantages, as notably discussed in Burns and Lee (2008) or in McKone-Sweet *et al.* (2005). However, some practical threats also exist, like the difficulty to gather a sufficient number of buyers (Liang *et al.*, 2014), or the reduced incentives for OEMs to innovate when they sell to GP organizations (Hu and Schwarz, 2011). Hu *et al.* (2012) and Saha *et al.* (2010) further study how those GP organizations affect healthcare supply chains.

The body of literature on GP has since then investigated strategic issues related to GP agreement, specially for competing retailers. Keskinocak and Savaşaneril (2008) find that, under Cournot competition, whether buyers would engage in group purchasing agreements would depend on their size and production capacity. Chen and Roma (2011) use a Bertrand model to show that, because of a reduced acquisition cost, GP is always beneficial for symmetric retailers, whereas it can be detrimental for one retailer if it has a larger market base (or if it is more cost efficient). For this retailer, letting its rival benefit from its better negotiating position (and hence lower purchasing cost) would erode its competitive advantage. In our paper, we examine the incentives for competing retailers to jointly procure from an information exchange perspective. Specifically, we study the mixed impact of uncertainty about both market demand and price sensitivity on the GP decision, where the price sensitivity uncertainty is attributed to the specific firm's uncertain product technology level. To the best of our knowledge, no extant work has studied this problem. Similar to our context, Yan *et al.* (2017) analyze the impact that asymmetric private information about demand has on retailers' attitude towards group purchasing. They find that the most informed retailer is never favorable to GP, suggesting that under information asymmetry, the cost benefits of GP do not compensate the loss of information advantage about the demand. In our work, we do not consider information asymmetry. However, we focus on the combined effect of two different types of uncertainties in motivating GP, rather than a single one as in Yan *et al.* (2017).

Finally, Group purchasing organizations (GPO) which play the role of intermediaries between buyers and suppliers have also received attention from academicians. Yang *et al.* (2017) and Zhou *et al.* (2017) investigate the incentives for buying firms to contract with a GPO or to share information with a GPO. However, in our paper the interaction is limited between the buying firms.

4.4 Individual purchasing case

We consider a duopoly with two OEMs represented by subscripts i and j. Both the OEMs simultaneously bring out a new product (which could be an upgrade to an existing product or a new generation of product) to the market. The demand for OEM i's product is modeled by its inverse demand as

$$p_i = P + \theta - \left(\frac{q_i + Kq_j}{M_i}\right), \tag{30}$$

with $P + \theta$ being the uncertain common market demand (where P is a constant and θ is a random variable with mean 0 and variance σ^2); $\frac{1}{M_i}$ is OEM i's price sensitivity to quantities brought to the market and K is product substitutability. We assume $K \in [0, 1]$ as an OEM is always more impacted by its own quantity decision than by its rival's, with $K = 0$ corresponding to independent markets and $K = 1$ to perfectly substitutable products.

As mentioned in the Introduction, prior to launching their respective products the competing OEMs are privately informed about their own product technology level. In our model, technology level can turn out to be high or low (based on the uncertain result of R&D program undertaken by the respective firms) with a likelihood of γ and $1 - \gamma$. To simplify the analysis, we assume that $\gamma = 0.5$, even though the main insights of our model would carry with any other value of γ. A low technology level of OEM i's product results in $M_i = 1$ and a high technology level of OEM i's product results in $M_i = M$, with $M \geq 1$. Thus M_i could either be 1 or M with a likelihood of 50% and is private information of OEM i. We interpret M as the market impact of technology and a higher value of M would represent a greater impact of high technology level product on OEMs' price and market shares relative to low technology level product. Actually, from a market perspective, it is maybe more the perception of the technology level that would influence the market shares rather than the technology level itself, such that *technological competitiveness uncertainty* might better suit our model than *technology uncertainty*. However, to simplify the terminology, we refer to this uncertainty as *technology uncertainty*. Further note that both γ and the value of M are exogenous, common knowledge and symmetric across OEMs. P and K are also exogenous and common knowledge.

Technology level is not the only source of private information that the OEMs would possess at the time of making their quantity decision. OEMs might also gain (private) information about other attributes that influence overall market demand as they move closer to introducing their product into the market. Specifically, before making the quantity decision each OEM receives a private signal Y_i, which is an unbiased estimator of θ, i.e., $\mathbb{E}_{Y_i}[Y_i|\theta] = \theta$. This signal could, for example, arise from market research conducted independently by the OEMs to estimate the market demand. Similar to Li (1985), we assume a linear-expectation information structure, i.e. $\mathbb{E}_{\theta}[\theta|Y_i]$ is linear in Y_i. This information structure includes well-known conjugate pairs like normal-normal, beta-binomial and gamma-Poisson. For example, with the gamma-Poisson distribution, an OEM i would receive a signal Y_i derived from a Poisson distribution, which would then enable the OEM to formulate the gamma distribution of θ, since the distribution of θ is conditional upon the signal received by the OEM. We further define signal accuracy as $t = \dfrac{\mathbb{E}_{Y_i}[Var[Y_i|\theta]]}{\sigma^2}$. Note that we omit subscript

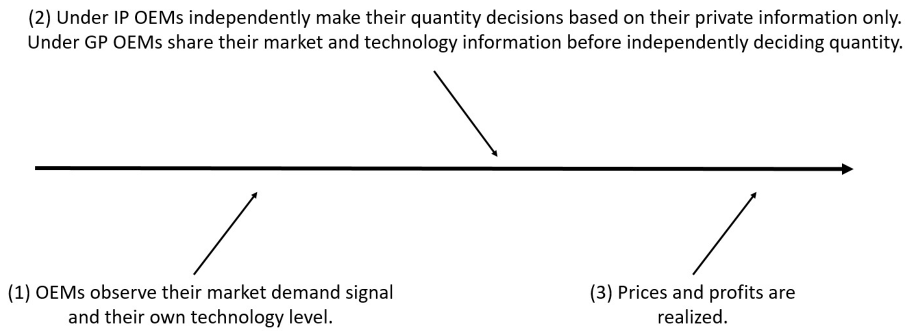

Figure 24: Timeline with the sequence of events.

from t since it is symmetric across OEMs and can take values between 0 and ∞, with 0 corresponding to a perfect signal, and ∞ corresponding to an uninformative signal. From Li (1985), we directly obtain that $\mathbb{E}_\theta[\theta|Y_i] = \mathbb{E}_{Y_j}[Y_j|Y_i] = \frac{Y_i}{1+t}$. Figure 24 depicts the Model timeline.

Under IP, an OEM i makes its quantity decision after having observed its own technology level (which directly gives M_i) and its own market demand signal, Y_i, but having no access to its competitor's private information. We denote OEM i's quantity decision in the IP case by $q_i^I(Y_i, M_i)$. Assuming that under IP each OEM incurs a symmetric per-unit purchasing cost $c^I < P$. We characterize OEM i's conditional expected profit as

$$\mathbb{E}_{M_j}\mathbb{E}_{Y_j}\mathbb{E}_\theta[\pi_i^I|Y_i, M_i] = q_i^I(Y_i, M_i)$$
$$\left(P + \mathbb{E}_\theta[\theta|Y_i] - \frac{1}{M_i}\left(q_i^I(Y_i, M_i) + K\mathbb{E}_{M_j}\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^I(Y_j, M_j)|Y_i]\right) - c^I\right). \tag{31}$$

Maximizing this conditional expected profit provides the equilibrium quantities under the IP case,[12] which are presented in Proposition 6. We

[12]Under both IP and GP, the quantity purchased by an OEM corresponds to the quantity that it finally sells on the market

assume $M < \frac{2}{K}$ such that the expected equilibrium quantities and prices are non-negative. In addition, we assume that P is sufficiently large as compared to σ, such that realized quantities and prices are almost always positive.

Proposition 6 *In the IP case, the unique equilibrium quantities for OEM i are characterized as*

$$q_i^I(Y_i, M_i = 1) = \frac{(P - c^I)\big(4 - K(M-1)\big)}{4(K+2)} + \frac{4(t+1) - K(M-1)}{4(t+1)(K+2(t+1))} Y_i,$$

$$q_i^I(Y_i, M_i = M) = \frac{(P - c^I)\big(4M + K(M-1)\big)}{4(K+2)} + \frac{4M(t+1) + K(M-1)}{4(t+1)(K+2(t+1))} Y_i.$$

Moreover, OEM i's expected profit, i.e. before it observes its technology level and market demand signal, is characterized as

$$\mathbb{E}\pi_i^I = \frac{(M+1)}{32M} \left\langle \frac{(P-c^I)^2}{(K+2)^2}\big(K^2(1-M)^2 + 16M\big) + \sigma^2 \frac{\big(16M(t+1)^2 + K^2(1-M)^2\big)}{(t+1)\big(K+2(t+1)\big)^2} \right\rangle. \tag{32}$$

Equation (32) characterizes OEM's ex-ante profit, i.e., before it observes its technology level and its market demand signal. We will later compare this expected profit with OEM's expected profit in the GP case to characterize OEM's decision to enter into a GP agreement or not.

4.5 Group purchasing case

Competing firms may decide to jointly procure a common component, that both of them need in their final product, from a single supplier. In such situation both the OEMs enter into a GP agreement in which they decide individually their respective order quantity, which they then pool into a joint order quantity that they place to their selected supplier. Compared to individually procuring this component (see previous section) the GP agreement allows both the OEMs to reduce their per-unit cost of procuring the component. We model this by assuming $c^I > c^G$, with c^G being the per-unit purchasing costs under GP. Specifically, we define $c^G = (1-r)c^I$, with $r \in [0,1]$ being the per-unit rebate offered by the supplier to OEMs that would jointly procure.

Reaching an agreement on a joint order quantity would typically involve iterative discussions between the OEMs which would inevitably result in some exchange (or leakage) of private information that each OEM possesses about the common market and/or its product technology. By information exchange we do not necessarily mean that OEMs would voluntarily reveal their private information but rather that the OEMs would glean each other's information from the repeated interactions that they would have before agreeing on a joint order size. This is consistent with Hendrick (1997), as well as Nollet and Beaulieu (2005), who argue that sensitive information disclosure is one of the disadvantages of GP. Schotanus (2007) even shows through an empirical study that sensitive information disclosure is an important factor in discouraging private firms (more than public) to commit to GP agreements. Without getting into the details of this process of repeated interactions, we rather use a parsimonious model in which we assume that through GP agreements OEMs become fully aware of each other's private information, on both common market demand and their product technology level, when deciding on a joint order quantity. Specifically, each OEM would formulate its expectation of θ conditional on both signals (Y_i and

Y_j) and moreover would be informed about both M_i and M_j. Following Li (1985) we obtain that $\mathbb{E}_\theta[\theta|Y_i, Y_j] = \dfrac{Y_i + Y_j}{2+t}$. Thus their joint quantity decision would involve each OEM deciding its own order quantity, $q_i^G(Y_i, Y_j, M_i, M_j)$,[13] that maximizes the OEM's expected profit conditional on the OEM being informed of each other's information set. The OEMs procure their joint order quantity $q_i^G + q_j^G$ at a per-unit cost of c^G. Under the GP strategy, OEM i's conditional expected profit can be characterized as:

$$\mathbb{E}_\theta[\pi_i^G|Y_i, Y_j, M_i, M_j] = q_i^G(Y_i, Y_j, M_i, M_j) \\ \Big(P + \mathbb{E}_\theta[\theta|Y_i, Y_j] - \frac{1}{M_i}\Big(q_i^G(Y_i, Y_j, M_i, M_j) + Kq_j^G(Y_j, Y_i, M_j, M_i)\Big) - c^G\Big). \tag{33}$$

Note that a critical difference between Equation (31) and Equation (33) is that in the former (IP case) OEM i's expected profit is characterized from the expectation of the equilibrium quantity that OEM j would bring to the market (i.e., from $\mathbb{E}_{M_j}\mathbb{E}_{Y_j}\mathbb{E}_\theta q_j^I$) whereas in the latter (GP case) OEM i's expected profit is characterized directly by q_j^G. Maximizing this conditional expected profit for each OEM gives the equilibrium quantities under GP.

Proposition 7 *In the GP case, OEM i's unique equilibrium quantity can be characterized by*

$$q_i^G(Y_i, Y_j, M_i, M_j) = \frac{(2M_i - KM_j)}{4-K^2}\Big(P + \frac{Y_i + Y_j}{2+t} - c^G\Big).$$

OEM i's expected profit, i.e. before it observes its technology level

[13] Regardless the OEM that we consider, we denote quantity decisions in GP as being dependent on (Y_i, Y_j, M_i, M_j), such that we have $q_j^G(Y_i, Y_j, M_i, M_j)$.

and market demand signal, can be characterized as

$$\mathbb{E}\pi_i^G = \frac{\Big((P - c^G)^2 + \frac{2\sigma^2}{t+2}\Big)\Big(M+1\Big)\Big(K^2(M^2+1) + 8M(1-K)\Big)}{4M\Big(4-K^2\Big)^2}. \tag{34}$$

4.6 Comparison between individual and group purchasing

Having analyzed the IP and GP cases in the previous sections, we are now in a position to answer the question on when would an OEM select GP rather than IP and inversely? Typically, the decision to get into a GP agreement would be made on a strategic level since the OEMs would have to select their common supplier and then negotiate the contract (quantity and price) terms with the supplier long before they bring their product to the market. We therefore model that an OEM decides to join a GP agreement or purchase individually before observing its market demand signal or its technological level. To formulate this decision we compare the ex-ante, expected, profit of an OEM in the IP case (characterized in Equation (32)) with its expected profit for the GP case (characterized in Equation (34)).

We denote the difference in expected profits between GP and IP as $\Delta_{OEM} = \mathbb{E}\pi_i^G - \mathbb{E}\pi_i^I$, which is characterized as

$$\Delta_{OEM} = \frac{(M+1)\big(\sigma^2 f + h\big)}{32M(K^2-4)^2(t+1)(t+2)\big(K+2(t+1)\big)^2}, \tag{35}$$

where

$$\begin{aligned}
f &= \Big(256Mt(t+1)^2\Big)(1-2K) + 16K^2\Big((M^2+1)\big(4t^3+12t^2+11t+2\big) + M\big(8t^3-14t-4\big)\Big) \\
&+ 64K^3(t+1)\Big((t+1)(M^2+1)-2M\Big) - 8K^4\Big(M\big(2t^3+8t^2+12t+8\big) - (3t+4)(M^2+1)\Big) \\
&- K^6(1-M)^2(t+2),
\end{aligned}$$

$$\begin{aligned}
h &= (t+1)(t+2)(K+2t+2)^2 \\
&\quad \Big\langle K^2(1-M)^2\big(-K^2+4K+4\big)(P-c^I)^2 + 8\phi\big(K^2(M^2+1)+8M(1-K)\big)\Big\rangle,
\end{aligned} \tag{36}$$

$$\phi = c^I r\big(c^I r + 2(P-c^I)\big). \tag{37}$$

Proposition 8 *Δ_{OEM} is convex in M. Moreover, Δ_{OEM} is increasing in M for $\Delta_{OEM} \geq 0$.*

This proposition indicates that, as soon as GP is preferred over IP, a higher market impact of technology M makes GP increasingly attractive as compared to IP, and thus would never result in a change of preferred strategies from GP to IP. We next determine how other parameters influence OEMs profitability in GP relative to IP. We present in Figure 25 a surface illustrating the set of parameter combinations for which the OEMs are indifferent between either purchasing option (i.e. $\Delta_{OEM} = 0$). This surface separates the region where IP is preferred (below the surface), from the region where GP is preferred (above the surface). One can notice from Equation (35) that the sign of $\sigma^2 f + h$ completely determines the sign of Δ_{OEM} (the other factors of the fraction are positive) and hence one needs to focus only on analyzing $\sigma^2 f + h$ to characterize the regions of Figure 25, which we show in the next Theorem.

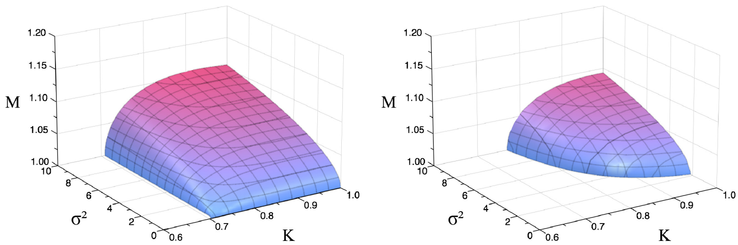

Figure 25: The surface represents situations in which OEMs are indifferent between IP and GP. GP (IP) is preferred above (below) this surface. On the left figure, $r = 0$, while $r = 0.01$ on the right figure. The other parameters are $P = 10$, $t = 0.5$, and $c^I = 0.5$.

Theorem 2 *GP is preferred over IP if $K \leq K^*$, with K^* being defined as*

$$K^* = \left| \frac{2(t+1)(\sigma^2 t - \phi(t+2)) - 2\sigma t\sqrt{(t+1)(t+2)(2\sigma^2 + \phi(t+2))}}{\phi(t+2) - \sigma^2 t(3+t)} \right|, \tag{38}$$

and with K^* being always greater than $\frac{2}{3}$. Otherwise, there exists a threshold M^* such that GP is preferred over IP if $M > M^*$, whereas IP is preferred over GP if $M < M^*$.

This result shows that whether IP or GP would be preferable critically depends on the value of the exogenous parameters K and M. The first part of theorem 2 provides the condition ($K < K^*$) under which GP dominates IP for any value of the market impact of technology M. This condition (i.e. $K < K^*$) implies that competing OEMs would be willing to share information as long as substitutability between their respective products is below a certain threshold (K^*). For the special case of $M = 1$, i.e., when there is no technology level uncertainty, Vives (1984) also finds a similar result in which OEMs should share market demand information as long as product substitutability is low enough. The reason for this comes from the information sharing dimension of GP, which has two effects: 1) on the one hand, it hurts OEMs' expected profits by perfectly correlating their quantity decisions but 2) on the other hand, it increases OEMs' expected profits since they can make more informed decision on their production quantity. While the benefits of sharing information (i.e. precision effect) are always attractive, its cost (i.e. correlation effect) depends on the value of K. If K is low, OEMs operate in rather independent markets and hence do not suffer from having correlated strategies (see Equation (30)), making GP more attractive. However, IP tends to be favored more often as substitutability between the products increases (i.e., as K increases). Actually, Theorem 2 confirms that OEMs competing on rather independent markets (i.e. low level of product substitutability K) are not penalized by exchanging sensitive private information (regardless whether it is information on common market demand or on product technology level), but that they rather benefit from making more informed decisions. Finally, comparing the left and right panels of Figure 25 we find that increasing the purchasing cost rebate r indeed results in GP being increasingly preferred over IP.

In the second part of Theorem 2, we show that even for $K > K^*$ GP could *still* be preferred over IP if the market conditions are such that $M > M^*$.[14] Interestingly, this result complements the earlier results in

[14]We provide the expression for M^* in the proof of Theorem 2 in appendix.

Economics literature Vives (1984) which state that OEMs should not share information when product substitutability is high enough. The reason being that models in Economics literature have typically focused on information uncertainty on market attributes, like common market demand (which in our case is P). However, we also bring in information uncertainty on attributes that are associated with specific OEM, like the impact that an OEM's product technology can have on the market. If market is insensitive to product technology (low M), i.e., the relative difference in the technological specification of the competing OEMs product does not influence their respective demand, then our model is similar to the traditional Economics model. However, typically the difference in technological specs of competing products would influence their respective demand and if a better product (by better we mean a product that has more advanced technological specs) has greater impact on demand (i.e., a high M) then we find that OEMs might be interested in sharing their information with each other even when their respective products have high substitutability. Namely, unlike with common market demand uncertainty alone, with both types of uncertainty considered simultaneously, product substitutability is not a sufficient criterion to guarantee that IP can be preferred over IP. Rather, to draw such conclusion, the substitutability has to be examined in parallel with market demand variability and with supplier rebate. Evidently the existence of a threshold value of M^* echoes the result of Proposition 8 in which the difference in OEMs' profit with GP relative to IP was increasing in M (for $\Delta_{OEM} > 0$).

To further understand the trade-offs in sharing information on technology versus sharing information on common market demand we next investigate how uncertainty about technology level alone would affect the purchasing strategy choice of the OEMs. For this, we set $\sigma^2 = 0$ (in which case t has no impact anymore).

Proposition 9 *When technology level is the only source of uncertainty, OEMs always prefer to share information.*

Proposition 9 claims that, without market demand uncertainty, OEMs are always better off sharing information through GP, even when the supplier does not offer any rebate in counterpart. This can be explained by the interactions that our model allows between competitors. Under GP, the OEMs would make their quantity decision while knowing both their own and their rival's technology levels. If an OEM has a technology advantage over the other, it would make a bigger order, to put its competitor under pressure, since OEMs affect each other's price through the quantity of products that they put on the market. In response, the rival would reduce its order to avoid flooding the market. Thus, technology level information makes OEMs' quantity decisions less correlated, which is profitable under Cournot. Specifically, the higher the market impact of technology, the more each OEM can put pressure on the other when it has a technology advantage, and the less correlated are the equilibrium decisions. In contrast, with only market demand uncertainty, OEMs prefer not to share information. Therefore in Theorem 2 we find that when both common market demand and OEMs' technology level are uncertain then a higher value of M (indicating higher uncertainty on technology) results in sharing of information between OEMs more beneficial, such that M offsets the disadvantages of sharing information due to uncertainty on common demand.

Next, we examine the sensitivity of Δ_{OEM} in the parameters r and P.

Proposition 10 *The difference in expected profits between GP and IP, i.e.* Δ_{OEM}*, is:*

(1) increasing in r*, while* M^* *is decreasing in* r*;*

(2) increasing in P*, while* M^* *is decreasing in* P*.*

We unsurprisingly find that Δ_{OEM} increases in the per-unit purchasing cost rebate arising from GP, i.e. r, such that with higher supplier rebate, GP gets more attractive relative to IP. Therefore, higher rebates would make GP preferred over IP for lower values of the market impact of technology M, and hence would result in a lower threshold value M^*. This can be visualized by comparing the left and the right plots of Figure 25.

As discussed after Theorem 2, uncertainty on common market demand incentivizes competing OEMs to conceal their private information, and thus to favor IP rather than GP. Especially, if the information on the market demand would be more uncertain, the information on common market demand would be even more valuable, and the suppliers would be even less willing to disclose it. On the contrary, a higher value of P would lower the effect of common market demand uncertainty, and would thus make GP preferred over IP more often, such that Δ_{OEM} is increasing in P. Note that, similar to r, the effect that P has on the threshold M^* introduced in Theorem 2 is the opposite of their effect on Δ_{OEM} such that M^* decreases in P.

4.7 Discussion on consumer welfare

Information sharing, and more generally cooperation, among rival OEMs would typically raise antitrust concerns if the related benefits derived by the OEMs would come at the detriment of the consumers. It is therefore interesting to examine whether GP can be favorable simultaneously for both the OEMs and the consumers, which is investigated in this section. We define consumer surplus for either IP or GP case as $\frac{(P+\theta-p_i)q_i}{2}+\frac{(P+\theta-p_j)q_j}{2}$ and characterize the expected consumer surplus in, respectively, the IP and the GP situations as:

$$\begin{aligned}
\mathbb{E}CS^I &= \mathbb{E}_{M_i}\mathbb{E}_{M_j}\mathbb{E}_\theta\mathbb{E}_{Y_i}\mathbb{E}_{Y_j}\frac{1}{2M_i}\Big(q_i^I(Y_i,M_i)+Kq_j^I(Y_j,M_j)\Big)q_i^I(Y_i,M_i) \\
&+ \mathbb{E}_{M_i}\mathbb{E}_{M_j}\mathbb{E}_\theta\mathbb{E}_{Y_i}\mathbb{E}_{Y_j}\frac{1}{2M_j}\Big(q_j^I(Y_j,M_j)+Kq_i^I(Y_i,M_i)\Big)q_j^I(Y_j,M_j), \quad (39)
\end{aligned}$$

$$\begin{aligned}
\mathbb{E}CS^G &= \mathbb{E}_{M_i}\mathbb{E}_{M_j}\mathbb{E}_\theta\mathbb{E}_{Y_i}\mathbb{E}_{Y_j} \\
&\quad \frac{1}{2M_i}\Big(q_i^G(Y_i,Y_j,M_i,M_j)+Kq_j^G(Y_i,Y_j,M_i,M_j)\Big)q_i^G(Y_i,Y_j,M_i,M_j) \\
&+ \mathbb{E}_{M_i}\mathbb{E}_{M_j}\mathbb{E}_\theta\mathbb{E}_{Y_i}\mathbb{E}_{Y_j} \\
&\quad \frac{1}{2M_j}\Big(q_j^G(Y_i,Y_j,M_i,M_j)+Kq_i^G(Y_i,Y_j,M_i,M_j)\Big)q_j^G(Y_i,Y_j,M_i,M_j). \quad (40)
\end{aligned}$$

By introducing the equilibrium quantities, as defined in Propositions 6 and 7, in the previous equations, we obtain $\Delta_{CS}{\equiv}\mathbb{E}CS^G-\mathbb{E}CS^I$, which is characterized as

$$\Delta_{CS}=\frac{(M+1)(\sigma^2 f_{CS}+h_{CS})}{32M^2(K^2-4)^2(t+1)(t+2)(K+2(t+1))^2}, \quad (41)$$

where

$$
\begin{aligned}
h_{CS} &= -(t+1)(t+2)(K+2t+2)^2\Big\langle K^2(M^2+1)\Big((P-c^I)^2(-K^2+4K+4)+8\phi\Big) \\
&\quad -M\Big(16\phi(K^3-2K^2+4)+2(P-c^I)^2K^2(-K^2+4K+4)\Big)\Big\rangle, \\
f_{CS} &= (M-1)^2(t+2)K^6-16Mt(t+1)K^5 \\
&+ \Big(16(-t^3+4t^2+8t+4)M-8(3t+4)(M^2+1)\Big)K^4 \\
&+ \Big(128(t^3+2t^2+2t+1)M-64(t+1)^2(M^2+1)\Big)K^3+256Mt(t+1)(K+t+1) \\
&- 16\Big((4t^3+12t^2+11t+2)(M^2+1)+2(4t^3+8t^2+t-2)M\Big)K^2. \qquad (42)
\end{aligned}
$$

Proposition 11 *The difference in expected consumer surplus between GP and IP, Δ_{CS}, is*

(1) non-negative when market demand is the only source of uncertainty.

(2) non-positive when technology level is the only source of uncertainty and when $r = 0$.

(3) increasing in r.

These results suggest that whether *GP* is desirable from the point of view of the consumers depends on the type of uncertainty faced by the OEMs. On the one hand, if market demand is the only source of uncertainty, we find that GP always benefits the consumers, which is consistent with Vives (1984), despite the fact that he does not take supplier rebate into account. On the other hand, in an environment with technology level uncertainty only, consumer surplus would decrease if OEMs commit to GP agreements, as long as the suppliers offer no rebate.

Interestingly, existing Economics literature (Vives, 1984) has found

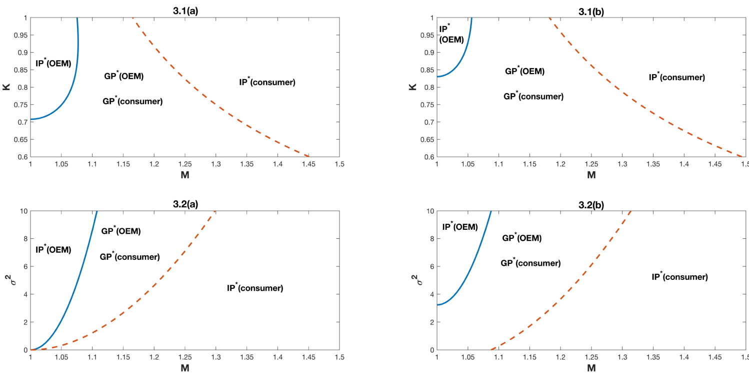

Figure 26: In the region between solid curve and dashed curve both OEMs and consumers are better off under GP. The parameters for 3.1(a) and 3.1(b) are $P = 10$, $t = 0.5$, $c^I = 0.5$, $\sigma^2 = 5$, $r = 0$ for (a) and $r = 0.01$ for (b). The parameters for 3.2(a) and 3.2(b) are $P = 10$, $t = 0.5$, $c^I = 0.5$, $K = 0.9$, $r = 0$ for (a) and $r = 0.01$ for (b).

that with market demand uncertainty only (and high enough product substitution K) OEMs do not prefer to share information and hence would not get into GP agreements even though GP agreement would benefit the consumer. On the other hand with technological level uncertainty only, Proposition 9 shows that OEMs would benefit from GP agreement, whereas consumer surplus might suffer specially when supplier rebate, r, in GP is low. This suggests that GP agreements can plausibly be beneficial to both OEMs and the consumers in cases where higher rebate offered by the supplier to the OEMs is partially passed to the consumers and when market demand uncertainty is not too high relative to technological level uncertainty. In the next Theorem we analyze precisely this, i.e., the situation in which GP agreement is beneficial to both the OEMs and the consumers.

Theorem 3 *There always exists a non empty interval in the market impact of technology M over which both consumers and OEMs simultaneously prefer GP over IP. This interval becomes larger as the supplier rebate r increases.*

We provide the implications of this theorem by first introducing M^*_{CS},[15] which is the threshold up to which consumers prefer GP and beyond which they prefer IP. In the proof of Theorem 3 we show that, $M^*_{CS} \geq M^*$ and therefore when OEMs sometimes prefer IP at $M = 1$ then the interval in which OEMs and consumers are simultaneously better off with GP is defined by $[M^*, M^*_{CS}]$. Otherwise when OEMs prefer GP at $M = 1$ then the interval in M over which OEMs and consumers both benefit from GP is defined by $[1, M^*_{CS}]$. It follows that there always exists an interval in M over which everyone benefits from GP. However, for high values of M, OEMs take advantage of GP agreements at the detriment of the consumers (i.e. when $M > M^*_{CS}$), whereas for low values of M, it can be that consumers benefit from GP at the detriment of the OEMs (i.e. when $1 \leq M < M^*$). Finally, we obtain that increases in the supplier rebate r result in a larger interval over which OEMs and consumers are better off together, as illustrated on Figure 26. These numerical results also suggest that the range of M, in which consumers and OEMs simultaneously favor GP, typically increases as market demand variability σ^2 increases or when product substitutability K decreases.

4.8 Conclusion

Although cost advantages for competing OEMs to get into GP agreements are well understood, other strategic aspects, specially information

[15]Similar to K^* and M^*, M^*_{CS} is a function of the model parameters.

sharing which is inherent to GP agreements, remain inaccurately understood. In this paper, we have investigated how the exchange of information about both market demand and technology level uncertainties that takes place when firms get into GP agreements, could affect their incentives to get into GP agreements. While Econmics literature has already found out that competing OEMs typically do not gain by exchanging information about market demand, little was known about the impact of sharing information on technology level, despite the fact that agreeing on common order size in GP agreements would involve information sharing on not only market demand estimates that each OEM possesses but also on each OEM's knowledge about the impact that its product specifications and technology would have on the market demand. This is specially relevant in markets where new versions of products are released periodically, i.e., OEMs do not know their rival's product technology level for the next period in advance, and hence can not anticipate the impact of their rival's product on their own demand for next period. In such markets, we have shown in this paper that when the uncertainty on technology is relatively high compared to uncertainty on market demand, then OEMs are always willing to share their technology level and market demand information and hence such situation might involve GP agreements. However, a lower level of technological uncertainty would not necessarily discourage OEMs to opt for GP, as this strategy would remain beneficial as long as either product substitutability is low, or if market demand uncertainty is sufficiently low relatively to the supplier rebate offered under GP.

In order to focus on impact that information sharing would have on competing OEMs' profitability we have assumed in this paper that GP agreements would involve OEMs fully sharing their information about their respective estimates of market demand and their technology level. In reality such an exchange of information might be more nuanced, since evidently the information is not directly communicated but is rather interpreted by OEMs from each other's order size which by themselves might be negotiated by OEMs prior to being given to a supplier. We do not model such a negotiation process between the firms but rather assume that an outcome of such an iterative negotiation process would result in each OEM having full information about the other OEM's private information. Future research on this topic could actually model such an iterative negotiation as a dynamic game to investigate the amount of information that OEMs would reveal in equilibrium through their order sizes. Such models could be further enriched if OEMs can order the same part from multiple suppliers while sharing just one supplier, as part of GP agreement. Although these models would be more detailed, the underlying tension in exchange of information would remain same as our paper, i.e., OEMS would be reluctant to part with their information on common market estimates but would be more willing to share information on their respective product technology.

There is a fine line between sharing information and collusion and/or anti-competitive practices, hence it is also necessary to measure the effect that information sharing would have on consumers' surplus, in order to determine whether GP could be conflicting with antitrust regulations. Our analysis shows that there always exists an interval for the market impact of technology over which the consumers and the OEMs would simultaneously benefit from GP agreements. Moreover, we obtain that this interval becomes larger as the rebate offered by the suppliers to

OEMs jointly purchasing increases. It follows that under such conditions GP can be beneficial for both OEMs and consumers

Our model could also be extended in various ways, as through considering a market with more than two OEMs or a multi-period model. We believe, however, that those two specific extensions would not result in different findings than those presented in this paper. Allowing for more sophisticated purchasing strategies than IP or GP could also be investigated. For example, OEMs could be given the option to make parallel orders to GP, as a mean to avoid revealing their private information.

Appendix

Proof of Proposition 6

Using Equation (31), we characterize the FOCs of $\mathbb{E}_\theta \mathbb{E}_{M_j} \mathbb{E}_{Y_j} \left[\pi_i^I | Y_i, M_i \right]$ and $\mathbb{E}_\theta \mathbb{E}_{M_i} \mathbb{E}_{Y_i} \left[\pi_j^I | Y_j, M_j \right]$ for each technology level as:

$$2q_i^I(Y_i, M_i = 1) = P - c^I + \mathbb{E}_\theta[\theta|Y_i] - \frac{K}{2}\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^I(Y_j, M_j = 1) + q_j^I(Y_j, M_j = M)|Y_i] \quad (43)$$

$$\frac{2}{M}q_i^I(Y_i, M_i = M) = P - c^I + \mathbb{E}_\theta[\theta|Y_i] - \frac{K}{2M}\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^I(Y_j, M_j = 1) + q_j^I(Y_j, M_j = M)|Y_i] \quad (44)$$

$$2q_j^I(Y_j, M_j = 1) = P - c^I + \mathbb{E}_\theta[\theta|Y_j] - \frac{K}{2}\mathbb{E}_{Y_i}\mathbb{E}_\theta[q_i^I(Y_i, M_i = 1) + q_i^I(Y_i, M_i = M)|Y_j] \quad (45)$$

$$\frac{2}{M}q_j^I(Y_j, M_j = M) = P - c^I + \mathbb{E}_\theta[\theta|Y_j] - \frac{K}{2M}\mathbb{E}_{Y_i}\mathbb{E}_\theta[q_i^I(Y_i, M_i = 1) + q_i^I(Y_i, M_i = M)|Y_j] \quad (46)$$

In order to solve the above system of equations we first assume a specific form of equilibrium quantities (that are linear in market demand signal); we then characterize these quantities. Finally we show that these are indeed a unique solution to the above equations and hence we formulate an equilibrium. We define the linear candidate strategies as

$q_i^I(Y_i, M_i = M) = H_i^0 + H_i^1 Y_i$, $q_i^I(Y_i, M_i = 1) = L_i^0 + L_i^1 Y_i$, $q_j^I(Y_j, M_j = M) = H_j^0 + H_j^1 Y_j$ and $q_j^I(Y_j, M_j = 1) = L_j^0 + L_j^1 Y_j$. Inserting these expressions into Equation (43) to (46) gives us 4 equations that are linear in Y_i (since q_i and q_j are linear in Y_i and Y_j respectively and moreover $\mathbb{E}_{Y_j}[Y_j|Y_i]$ too is linear in Y_i). By separating out terms containing Y_i and those not containing Y_i we obtain the following 8 equations :

$$2L_i^0 = (P - c^I) - \frac{K}{2}(L_j^0 + H_j^0) \tag{47}$$

$$2L_i^1 = \frac{1}{t+1} - \frac{K}{2(t+1)}(L_j^1 + H_j^1) \tag{48}$$

$$\frac{2}{M}H_i^0 = (P - c^I) - \frac{K}{2M}(L_j^0 + H_j^0)$$

$$\frac{2}{M}H_i^1 = \frac{1}{t+1} - \frac{K}{2M(t+1)}(L_j^1 + H_j^1)$$

$$2L_j^0 = (P - c^I) - \frac{K}{2}(L_i^0 + H_i^0)$$

$$2L_j^1 = \frac{1}{t+1} - \frac{K}{2(t+1)}(L_i^1 + H_i^1)$$

$$\frac{2}{M}H_j^0 = (P - c^I) - \frac{K}{2M}(L_i^0 + H_i^0)$$

$$\frac{2}{M}H_j^1 = \frac{1}{t+1} - \frac{K}{2M(t+1)}(L_i^1 + H_i^1)$$

Solving this system of equations gives

$$\begin{aligned}
L^0 &= L_j^0 = L_i^0 = \frac{(P - c^I)\big(4 - K(M-1)\big)}{4(K+2)} \\
L^1 &= L_j^1 = L_i^1 = \frac{4(t+1) - K(M-1)}{4(t+1)(K+2(t+1))} \\
H^0 &= H_j^0 = H_i^0 = \frac{(P - c^I)\big(4M + K(M-1)\big)}{4(K+2)} \\
H^1 &= H_j^1 = H_i^1 = \frac{4M(t+1) + K(M-1)}{4(t+1)(K+2(t+1))}.
\end{aligned}$$

Inserting these values into q_i gives

$$
\begin{aligned}
q_i^I(Y_i, M_i = 1) &= \frac{(P - c^I)\big(4 - K(M-1)\big)}{4(K+2)} + \frac{4(t+1) - K(M-1)}{4(t+1)(K+2(t+1))} Y_i. \\
q_i^I(Y_i, M_i = M) &= \frac{(P - c^I)\big(4M + K(M-1)\big)}{4(K+2)} + \frac{4M(t+1) + K(M-1)}{4(t+1)(K+2(t+1))} Y_i.
\end{aligned} \tag{49}
$$

Similarly, expressions for q_j are derived by substituting Y_i with Y_j in the above equations.

Next, we show the uniqueness of above linear equilibrium quantities. For this, we suppose $q_i^{I^*}(Y_i, M_i = M)$, $q_i^{I^*}(Y_i, M_i = 1)$, $q_j^{I^*}(Y_j, M_j = M)$, $q_j^{I^*}(Y_j, M_j = 1)$ is another equilibrium, i.e., they solve Equation (43). Reformulating Equation (43) with $q_i^{I^*}, q_j^{I^*}$ and then subtracting $2q_i^I(Y_i, M_i = 1)$ from both sides gives

$$
\begin{aligned}
&2(q_i^{I^*}(Y_i, M_i = 1) - q_i^I(Y_i, M_i = 1)) \\
&= P - c^I - 2L_i^0 + Y_i(\frac{1}{1+t} - 2L_i^1) - \frac{K}{2}\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = 1) \\
&+ q_j^{I^*}(Y_j, M_j = M)|Y_i].
\end{aligned}
$$

From Equation (47) we get $(P - c^I) - 2L_i^0 = \frac{K}{2}(L_j^0 + H_j^0)$ and from Equation (48) we get $\frac{1}{t+1} - 2L_i^1 = \frac{K}{2(t+1)}(L_j^1 + H_j^1)$. Therefore

$$
\begin{aligned}
&2(q_i^{I^*}(Y_i, M_i = 1) - q_i^I(Y_i, M_i = 1)) \\
&= \tfrac{K}{2}(L_j^0 + H_j^0) + \tfrac{K}{2(1+t)}(L_j^1 + H_j^1)Y_i - \tfrac{K}{2}\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = 1) \\
&+ q_j^{I^*}(Y_j, M_j = M)|Y_i].
\end{aligned}
$$

We know that

$$
\begin{aligned}
&\tfrac{K}{2}(L_j^0 + H_j^0) + \tfrac{K}{2(1+t)}(L_j^1 + H_j^1)Y_i = \tfrac{K}{2}(L_j^0 + L_j^1\tfrac{Y_i}{(1+t)}) + \tfrac{K}{2}(H_j^0 + H_j^1\tfrac{Y_i}{(1+t)}) \\
&= \tfrac{K}{2}(L_j^0 + L_j^1\mathbb{E}_{Y_j}[Y_j|Y_i]) + \tfrac{K}{2}(H_j^0 + H_j^1\mathbb{E}_{Y_j}[Y_j|Y_i]) \\
&= \tfrac{K}{2}\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^I(Y_j, M_j = 1) + q_j^I(Y_j, M_j = M)|Y_i].
\end{aligned}
$$

Therefore,

$$\begin{aligned}
&2(q_i^{I^*}(Y_i, M_i = 1) - q_i^I(Y_i, M_i = 1)) \\
&= \tfrac{K}{2}\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^I(Y_j, M_j = 1) + q_j^I(Y_j, M_j = M)|Y_i] \\
&-\tfrac{K}{2}\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = 1) + q_j^{I^*}(Y_j, M_j = M)|Y_i] \\
&= -\tfrac{K}{2}(\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = 1) - q_j^I(Y_j, M_j = 1)|Y_i] \\
&+\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = M) - q_j^I(Y_j, M_j = M)|Y_i]).
\end{aligned} \tag{50}$$

Similarly, reformulating Equation (44) with $q_i^{I^*}, q_j^{I^*}$ and then subtracting $\frac{2}{M}q_i^I(Y_i, M_i = M)$ from both sides, and then following the same steps as above gives

$$\begin{aligned}
&\frac{2}{M}(q_i^{I^*}(Y_i, M_i = M) - q_i^I(Y_i, M_i = M)) \\
&= -\frac{K}{2M}(\mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = 1) - q_j^I(Y_j, M_j = 1)|Y_i] \\
&+ \mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = M) - q_j^I(Y_j, M_j = M)|Y_i]).
\end{aligned} \tag{51}$$

From Equations (45), (46) we get:

$$q_j^{I^*}(Y_j, M_j = M) = q_j^{I^*}(Y_j, M_j = 1) + \frac{M-1}{2}(P - c^I + \mathbb{E}_\theta[\theta|Y_j]) \tag{52}$$

and

$$q_j^I(Y_j, M_j = M) = q_j^I(Y_j, M_j = 1) + \frac{M-1}{2}(P - c^I + \mathbb{E}_\theta[\theta|Y_j]). \tag{53}$$

Subtracting Equation (52) from Equation (53) gives

$$q_j^{I^*}(Y_j, M_j = M) - q_j^I(Y_j, M_j = M) = q_j^{I^*}(Y_j, M_j = 1) - q_j^I(Y_j, M_j = 1). \tag{54}$$

Taking the expectation on both sides of Equation (54) conditional on Y_i, we have $E_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = M) - q_j^I(Y_j, M_j = M)|Y_i] = E_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = 1) - q_j^I(Y_j, M_j = 1)|Y_i]$. Therefore Equation (50) and Equation (51) can be rewritten respectively as

$$-\frac{2}{K}(q_i^{I^*}(Y_i, M_i = 1) - q_i^I(Y_i, M_i = 1)) = \mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = 1) - q_j^I(Y_j, M_j = 1)|Y_i] \quad (55)$$

$$-\frac{2}{K}(q_i^{I^*}(Y_i, M_i = M) - q_i^I(Y_i, M_i = M)) = \mathbb{E}_{Y_j}\mathbb{E}_\theta[q_j^{I^*}(Y_j, M_j = M) - q_j^I(Y_j, M_j = M)|Y_i]. \quad (56)$$

Let $g_i(Y_i) = q_i^{I^*}(Y_i, M_i = 1) - q_i^I(Y_i, M_i = 1)$, and $g_i'(Y_i) = q_i^{I^*}(Y_i, M_i = M) - q_i^I(Y_i, M_i = M)$, then Equation (55) and (56) are equivalent to

$$-\frac{2}{K}g_i(Y_i) = \mathbb{E}_{Y_j}\Big[g_j(Y_j)|Y_i\Big]$$

$$-\frac{2}{K}g_i'(Y_i) = \mathbb{E}_{Y_j}\Big[g_j'(Y_j)|Y_i\Big].$$

Since $| -\frac{2}{K} |> 1$, according to Claim 1 in the Appendix of Ha *et al.*, $g_i(Y_i) = 0$ and $g_i'(Y_i) = 0$ almost surely. Therefore $q_i^{I^*}(Y_i, M_i = 1) = q_i^I(Y_i, M_i = 1)$ and $q_i^{I^*}(Y_i, M_i = M) = q_i^I(Y_i, M_i = M)$.

This finishes to prove that Equations (49) give the unique equilibrium quantity decisions, which we present in Proposition 6.

We substitute Equations (43) to (46) into Equation (31) to further obtain OEMs' ex-post expected profit. For low and high technology levels respectively, these are given by

$$\mathbb{E}_{M_j}\mathbb{E}_{Y_j}\mathbb{E}_\theta[\pi_i^I|Y_i, M_i = 1] = \Big(q_i^I(Y_i, M_i = 1)\Big)^2 \quad (57)$$

$$\mathbb{E}_{M_j}\mathbb{E}_{Y_j}\mathbb{E}_\theta[\pi_i^I|Y_i, M_i = M] = \frac{1}{M}\Big(q_i^I(Y_i, M_i = M)\Big)^2. \quad (58)$$

The expected profit, as presented in Proposition 6, is then obtained by weighting Equations (57) and (58) according to the likelihood that each technology level is reached (i.e. $\gamma = 0.5$):

$$\begin{aligned}\mathbb{E}\pi_i^I &= \mathbb{E}_{Y_i}\Big[\frac{1}{2}\Big(L^0 + L^1 Y_i\Big)^2 + \frac{1}{2M}\Big(H^0 + H^1 Y_i\Big)^2\Big] \\ &= \frac{1}{2}(L^0)^2 + \frac{1}{2M}(H^0)^2 + \mathbb{E}_{Y_i}[Y_i](L^0 L^1 + \frac{1}{M} H^0 H^1) \\ &\quad + \mathbb{E}_{Y_i}[Y_i^2]\Big(\frac{1}{2}(L^1)^2 + \frac{1}{2M}(H^1)^2\Big).\end{aligned} \tag{59}$$

Since $\mathbb{E}_{Y_i}[Y_i] = 0$, then $\mathbb{E}_{Y_i}[Y_i^2] = Var[Y_i] = \mathbb{E}_{Y_i}\big[Var[Y_i|\theta]\big] + Var\big[\mathbb{E}_{Y_i}[Y_i|\theta]\big] = t\sigma^2 + \sigma^2 = (1+t)\sigma^2$. Substituting $\mathbb{E}_{Y_i}[Y_i]$, $\mathbb{E}_{Y_i}[Y_i^2]$, L^0, L^1, H^0, H^1 into Equation (59), we obtain

$$\mathbb{E}\pi_i^I = \frac{(M+1)}{32M}\Big\langle \frac{(P-c^I)^2}{(K+2)^2}\big(K^2(1-M)^2 + 16M\big) + \sigma^2 \frac{\big(16M(t+1)^2 + K^2(1-M)^2\big)}{(t+1)\big(K+2(t+1)\big)^2}\Big\rangle.$$

Proof of Proposition 7

From Equation (33) and for a given (Y_i, Y_j, M_i, M_j) we obtain the FOCs for OEM i and OEM j respectively as

$$\begin{aligned} P + \mathbb{E}_\theta[\theta|Y_i, Y_j] - \frac{K q_j^G(Y_i, Y_j, M_i, M_j) + 2q_i^G(Y_i, Y_j, M_i, M_j)}{M_i} - c^G = 0 \\ P + \mathbb{E}_\theta[\theta|Y_i, Y_j] - \frac{K q_i^G(Y_i, Y_j, M_i, M_j) + 2q_j^G(Y_i, Y_j, M_i, M_j)}{M_i} - c^G = 0. \end{aligned}$$

Solving the above two equations and substituting $\mathbb{E}_\theta\big[\theta|Y_i, Y_j\big] = \dfrac{Y_i + Y_j}{2+t}$, we obtain

$$q_i^G(Y_i, Y_j, M_i, M_j) = \frac{(2M_i - KM_j)}{4 - K^2}\Big(P + \frac{Y_i + Y_j}{2+t} - c^G\Big).$$

Inserting the FOCs back into Equation (33) we obtain OEM i's equilibrium conditional expected profit:

$$\mathbb{E}_\theta\Big[\pi_i^G|Y_i, Y_j, M_i, M_j\Big] = \frac{1}{M_i}\Big(q_i^G(Y_i, Y_j, M_i, M_j)\Big)^2.$$

Then, we find the expected profit trough weighting the different combinations of technology levels by their respective probabilities (since $\gamma = \frac{1}{2}$, any pair of M_i and M_j together would occur with a likelihood of $\frac{1}{4}$):

$$\begin{aligned}
&\mathbb{E}\pi_{i_{GP}} = \tfrac{1}{4}\Big\langle \mathbb{E}_\theta \mathbb{E}_{Y_i}\mathbb{E}_{Y_j}\Big[\Big(q_i^G(Y_i,Y_j,M_i=1,M_j=1)\Big)^2\Big] + \mathbb{E}_\theta \mathbb{E}_{Y_i}\mathbb{E}_{Y_j}\Big[\Big(q_i^G(Y_i,Y_j,M_i=1,M_j=M)\Big)^2\Big] \\
&+\tfrac{1}{M}\mathbb{E}_\theta \mathbb{E}_{Y_i}\mathbb{E}_{Y_j}\Big[\Big(q_i^G(Y_i,Y_j,M_i=M,M_j=1)\Big)^2\Big] + \tfrac{1}{M}\mathbb{E}_\theta \mathbb{E}_{Y_i}\mathbb{E}_{Y_j}\Big[\Big(q_i^G(Y_i,Y_j,M_i=M,M_j=M)\Big)^2\Big]\Big\rangle \\
&= \frac{(M+1)\mathbb{E}_\theta\mathbb{E}_{Y_i}\mathbb{E}_{Y_j}\Big[\Big((P-c^G)^2+\frac{Y_i+Y_j}{t+2}\Big)^2\Big]}{4\Big(2+K\Big)^2}\Big(1+\frac{4(1-K)}{(2-K)^2}+\frac{K^2(M^2-M+1)}{M(2-K)^2}\Big)
\end{aligned} \tag{60}$$

Since $\mathbb{E}_{Y_i} = \mathbb{E}_{Y_j} = 0$ and since Y_i and Y_j are conditionally independent, we have
$\mathbb{E}_{Y_iY_j}[Y_iY_j] = Cov[Y_i, Y_j] = \mathbb{E}\big[Cov[Y_i, Y_j|\theta]\big] + Cov\big[\mathbb{E}_{Y_i}[Y_i|\theta], \mathbb{E}_{Y_j}[Y_j|\theta]\big] = 0 + Cov(\theta,\theta) = \sigma^2$. Using these and $\mathbb{E}_{Y_i}[Y_i^2] = \mathbb{E}_{Y_j}[Y_j^2] = (1+t)\sigma^2$, we can write

$$\begin{aligned}
\mathbb{E}_{Y_i}\mathbb{E}_{Y_j} \quad & \Big[\Big((P-c^G)+\frac{Y_i+Y_j}{t+2}\Big)^2\Big] \\
= \quad & (P-c^G)^2 + \frac{\mathbb{E}_{Y_i}[Y_i^2] + \mathbb{E}_{Y_j}[Y_j^2] + 2\mathbb{E}_{Y_iY_j}[Y_iY_j]}{(t+2)^2} \\
= \quad & (P-c^G)^2 + \frac{2\sigma^2}{t+2}.
\end{aligned}$$

Inserting the above expression back into Equation (60) gives Equation (34).

Proof of Proposition 8.

From Equation (35), we define $\Omega(M) \equiv \sigma^2 f + h$ and $\xi \equiv 32(K^2-4)^2(t+1)(t+2)(K+2(t+1))^2$. Note that ξ is independent of M and strictly positive. Now $\Delta_{OEM} = \dfrac{(M+1)\Omega(M)}{M\cdot\xi}$ would be convex in M if $\frac{M+1}{M}\Omega(M) = (1+\frac{1}{M})\Omega(M)$ is convex. We can characterize Ω as a quadratic function of M:

$$\Omega(M) = \alpha M^2 + \beta M + \alpha, \tag{61}$$

with

$$\begin{aligned}
\alpha &= K^2\sigma^2\Big\langle 16\Big(4t^3+12t^2+11t+2\Big)+64K(t+1)^2+7K^2(3t+4)+K^2(2t+2) \\
&\qquad +(t+2)(K^2-K^4)\Big\rangle \\
&\quad +K^2(t+1)(t+2)(K+2(t+1))^2\Big((-K^2+4K+4)(P-c^I)^2+8\phi\Big) \qquad (62)\\
\beta &= 2\sigma^2\Big\langle 128t(t+1)^2(1-2K)+16K^2(4t^3-7t-2)-64K^3(t+1) \\
&\qquad -8K^4(t^3+4t^2+6t+4)+(t+2)K^6\Big\rangle \\
&\quad +2(t+1)(t+2)(K+2(t+1))^2\Big(32\phi(1-K)-K^2(-K^2+4K+4)(P-c^I)^2\Big). \qquad (63)
\end{aligned}$$

Given that $K \leq 1$ implies $\alpha \geq 0$, Ω is convex in M. Also $\frac{\Omega}{M} = \beta + (M + 1/M)\cdot\alpha$ is convex in M. Thus, Δ_{OEM} is convex in M for $M > 0$.

Differentiating Δ_{OEM} with respect to M gives

$$\begin{aligned}
&\xi \cdot \frac{d\Delta_{OEM}}{dM} = -\frac{\Omega(M)}{M^2} + \left(1+\frac{1}{M}\right)\frac{d\Omega(M)}{dM} \\
&= -\frac{\alpha}{M^2} + 2\alpha\cdot M + \beta + \alpha = \frac{\Omega(M)}{M} - \frac{\alpha}{M} - \frac{\alpha}{M^2} + \alpha\cdot M + \alpha \\
&= \frac{\Omega(M)}{M} + (M+1)\alpha\left(1-\frac{1}{M^2}\right),
\end{aligned}$$

which is non-negative for $\Omega \geq 0$ (which is true for $\Delta_{OEM} \geq 0$) and $M \geq 1$ (assumed). Hence Δ_{OEM} is increasing in M for $\Delta_{OEM} \geq 0$.

Proof of Theorem 2.

In this proof, we first focus on giving the conditions for which GP dominates IP for any value of M. In a second part, we show that when this is not the case, there exists a threshold M^* from which GP dominates IP.

Starting with the first part of this proof, we know that, from the proof of Proposition 8, once $\Delta_{OEM}(M) > 0$, it keeps increasing in M. Thus, if $\Delta_{OEM}(M = 1) > 0$, $\Delta_{OEM} > 0$ for any $M \geq 1$. Since from Equation (35), the sign of Δ_{OEM} is given by the sign of Ω, we first provide the conditions for $\Omega(M=1)>0$. Using Equation (61), (62) and (63) we find that,

$$\Omega(M=1)=16(t+1)(2-K)^2\Big\langle\sigma^2 t\Big(4(t+1)(1-K)-K^2(3+t)\Big)+(t+2)\Big(K+2(t+1)\Big)^2\phi\Big\rangle. \quad (64)$$

Since $16(t+1)(2-K)^2>0$, $\Omega(M=1)>0$ if the bracket of Equation (64) is positive, namely if

$$l(K)\equiv K^2\Big(-(3+t)t\sigma^2+(t+2)\phi\Big)+4K(t+1)\Big(-\sigma^2 t+(t+2)\phi\Big)+4(t+1)\Big(\sigma^2 t+(t+1)(t+2)\phi\Big)>0. \quad (65)$$

We know that $l(K=0)>0$ ($\phi>0$ since $c^I<P$). Moreover the two roots of $l(K)$ in K can be characterized as

$$K_{1,2}=\frac{2(t+1)(\sigma^2 t-\phi(t+2))\pm 2\sigma t\sqrt{(t+1)(t+2)(2\sigma^2+\phi(t+2))}}{\phi(t+2)-\sigma^2 t(3+t)}.$$

For $\phi\geq\frac{\sigma^2 t(t+3)}{t+2}$, $l(K)$ is convex in K. Given that $l(K=0)>0$, convexity of $l(K)$ implies that both the roots are either negative or both are positive. For $\phi\geq\frac{\sigma^2 t(t+3)}{t+2}$ we know that $\frac{2(t+1)(\sigma^2 t-\phi(t+2))-2\sigma t\sqrt{(t+1)(t+2)(2\sigma^2+\phi(t+2))}}{\phi(t+2)-\sigma^2 t(3+t)}<-1$, which implies that the other root is also negative. Which implies that $l(K)>0$ for all $K\geq 0$.

For $\phi<\frac{\sigma^2 t(t+3)}{t+2}$, $l(K)$ is concave in K. Given that $l(K=0)>0$, concavity of $l(K)$ implies that one root is negative and the other positive. Indeed, for $\phi<\frac{\sigma^2 t(t+3)}{t+2}$ the only positive root can be $\frac{2(t+1)(\sigma^2 t-\phi(t+2))-2\sigma t\sqrt{(t+1)(t+2)(2\sigma^2+\phi(t+2))}}{\phi(t+2)-\sigma^2 t(3+t)}>0$. Defining $K^*\equiv\left|\frac{2(t+1)(\sigma^2 t-\phi(t+2))-2\sigma t\sqrt{(t+1)(t+2)(2\sigma^2+\phi(t+2))}}{\phi(t+2)-\sigma^2 t(3+t)}\right|$, we can write that $l(K)\leq 0$ for $K\geq K^*$ when $\phi<\frac{\sigma^2 t(t+3)}{t+2}$. Since $K\in[0,1]$, irrespective of the value of ϕ one can write that $l(K)\geq 0$ if $K\leq K^*$.

We further show that for any $K<\frac{2}{3}$, $\Omega(M=1)>0$ such that $K^*\geq\frac{2}{3}$. For this, we rewrite Inequality (65) as

$$\sigma^2 t\Big(t(-K^2-4K+4)-3K^2-4K+4\Big)\geq-\phi(t+2)\Big(K+2(t+1)\Big)^2, \quad (66)$$

which is true if $t(-K^2 - 4K + 4) \geq 3K^2 + 4K - 4$. Since on the interval $K \in [0, \frac{2}{3}]$, $-K^2 - 4K + 4 \geq 0$ and $3K^2 + 4K - 4 \leq 0$, Inequality (66) is true for any $K < \frac{2}{3}$. Therefore $K^* \geq \frac{2}{3}$.

Concerning the second part of this proof, from Equation (61) we see that $\Delta_{OEM} > 0$ beyond a threshold value of M (since $\alpha > 0$). Thus if $\Omega(M = 1) < 0$ (and consequently $\Delta_{OEM} < 0$), for $K > K^*$ and knowing that Δ_{OEM} is convex in M (from Proposition 8) implies that Δ_{OEM} would be greater than 0 beyond a threshold M. This threshold is the highest root in M of Equation (61), namely $M^* = \frac{\sqrt{\beta^2 - 4\alpha^2} - \beta}{2\alpha}$.

Proof of Proposition 9

From Equation (35), the sign of Δ_{OEM} is given by the sign of $\sigma^2 f + h$. Without market demand uncertainty, $\sigma^2 = 0$ such that if h is positive, GP dominates. This is actually always true, as can be seen in Equation (36).

Proof of Proposition 10.

Equations (35) to (37) directly reveal that $\Omega = \sigma^2 f + h$ increases in both r and P, and hence that Δ_{OEM} increases in r and P, since the other terms of Δ_{OEM} are positive and independent of r and P. Moreover, from the second part of Theorem 2, we know that, if IP dominates GP at $M = 1$, there exists a threshold M^* from which GP dominates IP, which is given by the highest root of $\Omega(M)$. As $\Omega(M)$ is convex with a minimum, an increase (decrease) in $\Omega(M)$, for all values of M, would result in M^* being lower (higher). From the first part of this proof, we thus find that the threshold M^* is decreasing in r and in P (and is bounded at 1 since $M \geq 1$).

Proof of Proposition 11

Inserting the equilibrium quantities in Equations (39) and (40) enable us to find the equilibrium expected consumer surplus, and then the difference in expected consumer surplus between GP and IP, i.e. Δ_{CS}, as presented in Equation (41).

We define $\Omega_{CS} = \sigma^2 f_{CS} + h_{CS}$ such that, from Equation (41), the sign of Δ_{CS} is given by the sign of Ω_{CS}. We thus focus on analyzing Ω_{CS} for the two first points of Proposition 11 and find that

$$\Omega_{CS}(M=1) = 16(K-2)^2(t+1)\langle t\sigma^2\big(4(t+2K+1)+tK(4-K)+K^2-K^3\big)+\phi(K+1)(t+2)(K+2t+2)^2\rangle,$$

$$\Omega_{CS}(\sigma^2=0, r=0) = -(P-c^I)^2K^2(M-1)^2\big(t^2+3t+2\big)\big(-K^2+4K+4\big)\big(K+2t+2\big)^2,$$

with $\Omega_{CS}(M=1)$ being non-negative and $\Omega_{CS}(\sigma^2=0, r=0)$ non-positive for $K \in [0,1]$.

Regarding the last point of Proposition 11, from Equation (40), $\mathbb{E}CS^G$ increases in equilibrium quantities q_i^G, q_j^G. Since from Proposition 7 the equilibrium quantities are increasing in r (as c^G decreases in r), it follows that $\mathbb{E}CS^G$ increases in r. Moreover, $\mathbb{E}CS^I$ is independent of r. Therefore, $\Delta_{CS} = \mathbb{E}CS^G - \mathbb{E}CS^I$ increases in r.

Proof of Theorem 3

This proof is organized in 3 steps. First, we show that there exists a threshold $M^*_{CS}(\cdot) \geq 1$ such that consumers prefer GP to IP as long as $M < M^*_{CS}(\cdot)$ and prefer IP to GP when $M > M^*_{CS}(\cdot)$. For this, we write Ω_{CS} (from Equations (41) to (42)) as a quadratic function in M, such that $\Omega_{CS} = aM^2 + bM + a$, where

$$a = -K^2(t+1)(t+2)(K+2t+2)^2\Big((-K^2+4K+4)(P-c^I)^2+8\phi\Big)$$
$$-K^2\sigma^2\Big(-(t+2)K^4+8(3t+4)K^2+64(t+1)^2K+16t(4t^2+12t+11)+32\Big)$$

$$b = (t+1)(t+2)(K+2t+2)^2\Big(2(P-c^I)^2K^2(-K^2+4K+4)+16\phi(K^3-2K^2+4)\Big)$$
$$+2\sigma^2\Big(-(t+2)K^6-8t(t+1)K^5+8(-t^3+4t^2+8t+4)K^4+64(t^3+2t(t+1)+1)K^3$$
$$-16(4t^3+8t^2+t-2)K^2+128t(t+1)(K+t+1)\Big)$$

Given that $K \leq 1$ implies $a \geq 0$, which implies that Ω_{CS} is concave in M. Moreover, Ω_{CS} would be non-positive beyond a certain threshold value of M since $a < 0$. From Proposition 11, we know that $\Omega_{CS}(M=1) \geq 0$, and therefore there exists a unique square root $M^*_{CS} = \frac{-b+\sqrt{b^2-4a^2}}{2a} \geq 1$ above which $\Omega_{CS} < 0$.

The second part of this proof shows that there always exists an interval on which both consumers and OEMs are better off with GP, relatively to IP. Following Theorem 2, there can be two situations from the perspective of the OEMs. First, GP can dominate IP from $M = 1$ (and hence for any value of M). In that case, OEMs and consumers prefer GP if $M \in [1, M^*_{CS}]$, which is non empty as we have shown in the first part of this proof that $M^*_{CS} \geq 1$. Second, GP can be preferred by the OEMs only from a certain threshold M^*. We show this part of the proof by contradiction. Let us assume that $M^* > M^*_{CS}$. Then, since consumers prefer GP (IP) up to (beyond) M^*_{CS} and OEMs prefer GP (IP) beyond (up to) M^*, therefore for $M^*_{CS} < M < M^*$ we have $\Delta_{CS} < 0$ and $\Delta_{OEM} < 0$ which implies that $\Delta_{OEM} + \Delta_{CS} < 0$. From Equations (35) and (41) we characterize $\Delta_{OEM} + \Delta_{CS}$ as

$$\Delta_{OEM} + \Delta_{CS} = \frac{(M+1)\Big(\phi(t+2)\big(K+2(t+1)\big)+t\sigma^2(2-K)\Big)}{2(K+2)(t+2)(K+2(t+1))} \geq 0,$$

which contradicts our assertion that $M^* > M^*_{CS}$. As a consequence, $M^*_{CS} \geq M^*$, and hence both OEMs and consumers are better off over $M \in [M^*, M^*_{CS}]$.

In the third part of this proof, we demonstrate that the interval in M over which OEMs and consumers simultaneously prefer GP becomes larger as r increases. In the case where OEMs prefer GP for any M, since Δ_{CS} is concave with a maximum and increases in r (see point 3 of Proposition 11), M^*_{CS} increases in r, while OEMs would still prefer GP for any M. Consequently, the interval $[1, M^*_{CS}]$ becomes larger as r increases. If OEMs prefer IP up to M^*, then we know from Proposition 10 that M^* is decreasing in r. Moreover, from Proposition 11 we know that Δ_{CS} increase in r, which along with concavity of Δ_{CS} in M and the fact that $\Delta_{CS}(M = 1) > 0$ implies that M^*_{CS} would increase in r. Therefore, the interval $[M^*, M^*_{CS}]$ also becomes larger as r increases.

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5. Conclusion of the dissertation

In this dissertation, we have described the critical role of procurement, which aims at maintaining and developing comparative advantages in product availability, product cost competitiveness, as well as in product value development. To reach this objective, we have emphasized the necessity of managing procurement strategically, in order to cope with the current challenging environment and complex supply chain structures. Specifically, we have documented (some of) the available procurement levers that a firm can use when establishing its procurement strategy, as well as their implications for the various functions of the procurement in specific situations. Then, we have presented our three research projects, while highlighting how they insert in the existing literature and how their strategic dimension can support procurement in fulfilling its functions in the present context.

Because the importance of procurement inside organizations grows continuously, research on each of its three functions should remain abundant in the near future. Specifically, academicians interested in procurement are likely to concentrate some of their efforts on the major challenges that procurement will face in the near future. We present some of these in this paragraph. (1) First, while continuous cost reductions will remain a primary task of procurement, the focus might be directed towards the creation of value for the customers, notably through innovating and improving quality. Aiming at this, a major driver for end-product differentiation will be the ability of procurement to integrate the capabilities of various suppliers and make these collaborate together. (2) Also, real-time accurate information will become standard thanks to big data and real-time analytics. This will require more flexibility from procurement, to react to the information received, and more efficient information sharing along the supply chain. Data can be considered as a competitive weapon, but only if it is well exploited. (3) Firms sourcing globally will also have to manage the rapid development of China, as it produces a quarter of global manufacturing output by value (The Economist, 2015). With the increasing Chinese labor costs, some firms might be tempted to shift their production networks to lower-cost countries, to re-shore or next-shore manufacturing jobs. This phenomenon might be accentuated with robotics, as it would lead production costs to be less dependent on human work and hence less sensitive to labor costs. It is therefore not obvious whether the Chinese impact on the global manufacturing output will keep increasing or, on the contrary, whether it might start to get reduced.

The environment will further pose challenges along various directions. (4) The scarcity of some resources is likely to increase the competition (and the price) for some items or raw materials. This threat is actually an opportunity for firms leading the innovation, as these might adapt faster their product for not being dependent on those scarce resources. (5) If natural disasters keep occurring still more often and keep being more and more violent, procurement managers could be obliged to increasingly weight the product availability function of procurement over the two others, in order to secure the supply chain and ensure continuity of operations. (6) Finally, environmental and social considerations might transform the procurement role by requiring more circular supply chains. These likely evolutions in the environment will continuously put pressure on procurement managers to adapt their strategy to remain competitive. Moreover, as the world will keep changing faster and faster, the procurement practices will evolve at the same pace, such that the firms' ability to attract talented people to govern the procurement activity will reveal being a major challenge.

Leaning on these six potential changes, as well as on the literature review from Subsection 1.2, we discuss in the last paragraphs three directions that could be followed for our future research in procurement. A first opportunity would be to study the trade-off for a buying firm between keeping suppliers under pressure to obtain cost competitive supply and securing long-term supply. Because of the outsourcing trend, even critical functions like innovation are often outsourced to suppliers, resulting in a loss of skills from the buyer, which thus relies increasingly on its supply base. Therefore, such strategic suppliers would be in a more comfortable position to negotiate prices with the buyer. It would therefore be challenging to further investigate mechanisms allowing the buyer to maintain pressure on its suppliers, without threatening the long-term collaboration with these, except if the buyer has another valuable option. Notably, it would be interesting to investigate whether buyers would rather reverse the current outsourcing trend through vertically integrating such strategic suppliers, or if they would rather prefer to create barriers to keep some bargaining power with the supplier (i.e. partial integration of the supplier). Buyers' dependence on suppliers is a source of risk that becomes increasingly crucial with outsourcing practices. This situation would thus deserve more attention in the future to determine which mechanisms the buyer and/or the suppliers might want to implement. Moreover, this phenomenon is exacerbated by factors like resource scarcity or market concentration (i.e. mergers and acquisitions among suppliers).

A second direction that could be followed for future research is related to green supply chains. Although the green revolution has already begun, it is highly likely to become increasingly prevalent in the future, especially as it is driven simultaneously by both regulators and customers. The question is therefore not whether higher standards will be required from firms, but when those standards will become applicable. And at that moment, the firms that would have better managed the transition would have a comparative advantage over the competition. As we have seen that procurement plays an increasingly central role in the supply chain, it therefore presents an important potential for improvement towards greener supply chains, and hence for research, especially as very few analytical models on green procurement exist so far.

A central question on the environmental transition is how firms should manage the innovation (both in terms of technologies and processes). Two main issues that we have already considered in this dissertation then appear. First, one can wonder whether competing firms should cooperate through pooling their investments to reach faster and better benefits. Cooperating with rivals becomes more and more frequent, as a mean to reduce costs (i.e. innovation costs in this situation). However, the impact on competition across the firms pooling their investments would not be obvious and might deter firms from jointly investing if they do not define the right incentives for the different participants. Second, as firms tend to integrate as much as possible their suppliers' expertise in the innovation process, it might be unclear where the investments would be the most efficient: at the suppliers' side or at the firm's side? Notably both firms' financial ability to invest, as well as the risk of spillovers would be factors to be taken into account for such analysis.

Another challenge dealing with the environment would be to cope with resource scarcity, through securing enough supply on the long-term, or better anticipating the transition. For example, circular supply chains could sometimes become necessary to limit the utilization of some raw materials. However, as recycling would be a process with more variability (from the amount of utilized material that could be retrieved) than simply buying from suppliers, it could be interesting to wonder how circular supply chains could be coupled with traditional supply chains to balance green, cost and availability efficiency. Once again, jointly recycling with other firms might be an attractive option. Finally, we could also study how to optimally integrate the environmental criteria in procurement auctions. Namely, either a premium could be paid to the best performers on this criterion, or bad performers might be withdrawn from the auction. Designing auction mechanisms that motivate suppliers' investments to improve their environmental performance could also be an option to investigate.

Finally, a third direction that we would be tempted to further investigate deals with the flows of capital along a supply chain, since there is still a lack of understanding about the financing of operations when various participants constitute the supply chain. Notably, multiple rationale for the utilization of trade credit co-exist and sometimes conflict with each other, making it unclear when it should be utilized. Then, it could also be interesting to measure the financial risk along the whole supply chain and to study the optimal financing of the operations based on this level of risk. More generally, thinking the financing of the whole supply chain rather than linkage by linkage could be an important improvement. This might have different effects, such as reducing production cost, incentivizing suppliers' investments, creating stronger ties between supply chain participants, etc... With the same logic, other questions could also be investigated, such as the long-term impact of putting financial pressure on both strategic and non-strategic suppliers, the benefits from sharing the individual financial information along the supply chain, the type of signal sent through extending trade credit or yet the interactions between supply chain financing and competition.

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